SOURCES AND EFFECTS OF IONIZING RADIATION

United Nations Scientific Committee on the Effects of Atomic Radiation

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NOTE

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ANNEX C

RADIATION EXPOSURES IN ACCIDENTS

CONTENTS

INTRODUCTION

1. In the course of the research and development for and the application of atomic energy and nuclear technologies, a number of radiation accidents have occurred. Some of these accidents have resulted in significant health effects and occasionally in fatal outcomes. The application of technologies that make use of radiation is increasingly widespread around the world. Millions of people have occupations related to the use of radiation, and hundreds of millions of individuals benefit from these uses. Facilities using intense radiation sources for energy production and for purposes such as radiotherapy, sterilization of products, preservation of foodstuffs and gamma radiography require special care in the design and operation of equipment to avoid radiation injury to workers or to the public. Experience has shown that such technology is generally used safely, but on occasion controls have been circumvented and serious radiation accidents have ensued.

2. Reviews of radiation exposures from accidents have been presented in previous UNSCEAR reports. The last report containing an exclusive chapter on exposures from accidents was the UNSCEAR 1993 Report [U6].

3. This annex is aimed at providing a sound basis for conclusions regarding the number of significant radiation accidents that have occurred, the corresponding levels of radiation exposures and numbers of deaths and injuries, and the general trends for various practices. Its conclusions are to be seen in the context of the Committee's overall evaluations of the levels and effects of exposure to ionizing radiation.

4. The Committee's evaluations of public, occupational and medical diagnostic exposures are mostly concerned with chronic exposures of various population groups at levels that are well below the thresholds for early acute (deterministic) health effects. In contrast, accidents can involve relatively high exposures, above such thresholds, and it is necessary to consider separately the early acute health effects, which essentially occur only in accidents and which are clearly attributable to radiation exposure. In addition, a few accidents have led to elevated exposures among larger populations, usually by releasing radioactive material into the environment; the Committee has attempted to assess the contribution such accidents have made to overall population radiation exposures.

5. The scope of this annex was to include "a survey of accidents whereby exposure to radioactive material affected workers or members of the public in a fashion that results in acute (i.e. deterministic) health effects." Selected accidents of significant public interest and/or involving environmental contamination were also to be considered. Thus, for the purpose of this annex, radiation accidents are defined as unintended events in which at least one person experienced early acute health effects that required some degree of medical intervention, and unintended events that caused significant population exposures due to environmental contamination.

6. It should be noted that the Committee has not considered accidents that may have been significant from a technical point of view (e.g. failures in safety systems at nuclear power plants) but that did not lead to radiation exposures. Moreover, it is not the purpose of this annex, and indeed it is outside the remit of the Committee, to investigate the root causes of the accidents, analyse accident progressions, conduct probabilistic risk assessments and forecast trends. Nevertheless, in order to provide a better qualitative appreciation of the range of characteristics and common features of the accidents that have occurred, the Committee has provided brief summaries of selected accidents, their circumstances and their health consequences, and has described overall trends when possible.

7. Accidents were selected for inclusion in the text and/or tables if information about the accident was available in published literature in medicine, radiation protection or dosimetry, or other relevant scientific or government literature, or in publications of the International Atomic Energy Agency (IAEA) or the World Health Organization (WHO). Malicious acts (intentional as opposed to accidental), with one exception of topical interest (see paragraph 124), are not included in this compilation, nor are accidents that occurred during nuclear weapons testing. During the fifty-fifth session of the Scientific Committee, it was agreed that no descriptions of accidents occurring after July 2007 would be included in this annex.

8. The IAEA and WHO publish important documents related to accidents for which they have provided assistance in response; these documents contain extensive descriptions of the event, dose assessments, health consequences and medical treatment. Accident catalogues are maintained by the Institute of Biophysics, Moscow, Russian Federation; by SEARCH in Ulm, Germany; by the Curie Institute, Paris, France; and by REAC/TS in Oak Ridge, Tennessee, United States of America. Table 1

provides a summary of accidents recorded for the territory of the former Soviet Union, some of which are described in this report [M4].

9. The Committee considers it likely that most of the serious accidents at nuclear facilities have been reported. In contrast, it considers it probable that many smaller industrial accidents, accidents with “orphan” sources, accidents in academic or research work and very many accidents in the medical uses of radiation have not been reported. There may be various reasons for this, including cultural and professional attitudes, fear of prosecution and ineffective regulatory regimes. In any case, it is clear that this review of accidents cannot be considered comprehensive.

10. Nevertheless the Committee considers that its assessment does provide a depiction of the number of significant radiation accidents that have occurred, the corresponding levels of radiation exposures and numbers of deaths and injuries, and the general trends for various practices, as a basis for evaluating the contribution made by accidents to overall radiation exposures and effects.

11. The review of selected radiation accidents has six sections:

- Section I covers criticalities and other operational accidents occurring at nuclear facilities, including accidents resulting in releases to the environment.
- Section II describes accidents involving sources, accelerators and X-ray devices used in industrial facilities.
- Section III provides examples of accidents associated with orphan sources and devices.
- Section IV describes accidents involving sources and radiation-generating devices used in academic and research environments.
- Section V provides examples of medical accidents involving sources, radiation-generating devices and nuclear medicine.
- Section VI addresses other accidents, principally those connected with the transport and movement of radioactive and nuclear materials in land, air, sea, undersea and space vehicles.
- Section VII summarizes information about accidents in various practices.

I. ACCIDENTS AT NUCLEAR FACILITIES

12. Accidents at nuclear facilities are considered in two categories: those related to nuclear weapons programmes and those not related to nuclear weapons programmes. Each category is considered in three subsections:

- *Criticality accidents.* These are generally considered significant owing to the potential loss of special nuclear material, serious contamination of the workplace, the possibility of off-site contamination and, in some cases, serious medical consequences. A large number of such accidents have occurred, although most of them took place in the early research and development of nuclear weapons technologies. This annex summarizes only those criticality accidents that led to serious medical consequences, and tables 2a and 2b summarize information on the 23 criticality accidents that have been reported.
- *Other accidents with only on-site consequences.* These have occurred during operations at nuclear facilities, and affected principally on-site workers. Some also involved the release of radioactive material to the outside environment and possible exposure of off-site populations. Tables 2a and 2b summarize key information on eight such accidents (other than criticality accidents) that led to early health effects among operators, plant staff or emergency response personnel, but had no significant off-site exposures of the general population or environment.
- *Accidents with releases to the environment and potentially significant population exposures.* Tables 2a and 2b summarize key information on seven accidents (including one criticality accident) at nuclear facilities that resulted in significant exposures of the general public.

A. Accidents related to nuclear weapons programmes

1. Criticality accidents

13. Of the 23 criticality accidents in total that have been reported, 17 occurred at facilities related to nuclear weapons programmes, which are listed in table 2a and briefly described below.

14. *United States, Los Alamos National Laboratory, 1945.* Three serious accidents have occurred at Los Alamos National Laboratory in Los Alamos, New Mexico. The first occurred in August 1945 when a critical assembly was being created by stacking tungsten carbide bricks around a plutonium core. The experimenter was moving the final block into place when he noted the neutron count indicating that the addition of the last brick would make the assembly supercritical. As he withdrew his hand, the final brick slipped and fell into the centre, creating the criticality. His dose[1] was estimated at 5.1 Gy from

[1] Dose, unless otherwise specified, refers to whole-body dose.

a yield of 10^{16} fissions. He died 28 days after the exposure. An army guard assigned to the building but not directly involved with the experiment received a dose estimated at 0.5 Gy [L1].

15. *United States, Los Alamos National Laboratory, 1946.* In May 1946, the plutonium core described above was being used in a demonstration of the techniques for creating a metal critical assembly using beryllium as a reflector. The individual conducting the demonstration was holding the top cell with his left thumb and inadvertently allowed one edge of the upper hemisphere to come into contact with the lower hemisphere. He attempted to place a screwdriver under part of the upper hemisphere not in contact with the lower hemisphere. The screwdriver slipped, resulting in a criticality excursion with an estimated yield of 3×10^{15} fissions. The individual conducting the experiment died nine days after the exposure, following a dose estimated at 21 Gy. Seven other individuals in the room received doses ranging from 0.37 to 3.6 Gy [L1].

16. *United States, Argonne National Laboratory, 1952.* In June 1952, an accident occurred at Argonne National Laboratory in Argonne, Illinois, in a light water moderated core in which 6.8 kg of ^{235}U oxide was embedded in strips of polystyrene plastic. The system became critical following an attempt to replace the control rod when the normal amount of water was in the core. Four individuals received radiation doses of 1.36, 1.27, 0.6 and 0.09 Gy [L1].

17. *Former Soviet Union, Mayak Complex, 1953.* In March 1953, a criticality excursion occurred at the Mayak Complex in Chelyabinsk involving seven 40 L tanks of unfavourable geometry used for the mixing, dilution, sample storage and transfer of plutonium nitrate derived from irradiated reactor fuel. No radiation monitoring equipment was available to workers; therefore the seriousness of the event was not recognized. The estimated yield was 2.5×10^{17} fissions. An operator received about 10 Gy whole-body dose, but this was very non-uniform (more than 30 Gy to the legs). He survived a moderate degree of acute radiation syndrome (ARS) but amputation of both legs was necessary. The dose to a second operator was about 1.5–2.0 Gy and she survived a mild degree of ARS [G5, L1, V1].

18. *Former Soviet Union, Mayak Complex, 1957.* In April 1957, a second event occurred involving a tank used for oxalate purification and filtration of highly enriched uranium solutions. An unsafe geometry resulted in a criticality with a fission yield estimated at 2×10^{17}. The operator, who remained in the area for approximately ten minutes, died 12 days later, having received a whole-body dose estimated at about 10 Gy (based on an analysis of the ^{24}Na levels in his blood). Five other workers experienced ARS of different severities depending on the doses received, which ranged from 2.0 to 6.0 Gy [G5, L1, V1].

19. *Former Soviet Union, Mayak Complex, 1958.* In January 1958, a third event occurred that was related to the use of a test tank built for determining critical parameters for solutions of uranium. After a test, a team of four persons decided to speed the draining of a solution. The combination of the solution geometry in the tank and neutron reflection by the workers' bodies resulted in a criticality involving approximately 2.3×10^{17} fissions. Three of the four persons died within one week, with doses estimated to have been in the range 40–50 Gy. The fourth person, who had been 3 m away from the tank, received a dose estimated at 6 Gy and presented symptoms of ARS and of visual impairment. She survived, although long-term health problems related to organs on the left side of her body were observed, including skin fibrosis, kidney sclerosis and cataracts [B11, G5, K2, L1, V1].

20. *United States, Y-12 plant, 1958.* In June 1958, a criticality accident occurred at the Y-12 plant in Oak Ridge, Tennessee, during recovery of enriched uranium from various solid wastes. Prior to the accident and unbeknown to anyone, uranyl nitrate had been collecting in a vessel because of a leaking valve. When an operator opened the vessel to drain water into a 55 gallon (208 L) drum, the water was preceded by the enriched uranium solution. The unsafe geometry in the drum resulted in a criticality excursion with an estimated yield of 6×10^{16} fissions. A second excursion occurred 15 seconds later. Eight male workers (aged 25 to 56 years) were exposed, with five of the men receiving whole-body doses of between 2.36 and 3.65 Gy. Three others received doses of below 0.7 Gy. Long-term follow-ups with annual medical evaluations were conducted [A1].

21. *United States, Los Alamos National Laboratory, 1958.* In December 1958, a third accident at Los Alamos National Laboratory occurred during an annual physical inventory when process streams were interrupted in a unit used to purify and concentrate plutonium from slag, crucible and other lean residues from recovery processes. Dilute aqueous and organic solutions from two vessels were washed into a single large vessel. The addition of a nitric acid wash to the tank is believed to have separated the liquid phases, resulting in an excursion when a stirrer was activated. The excursion had a yield of 1.5×10^{17} fissions. The accident resulted in the death of the operator 36 hours after exposure, with a dose to the upper torso estimated at approximately 120 Gy. Two other individuals suffered no ill effects after doses estimated at 1.34 and 0.53 Gy [L1].

22. *United States, National Reactor Testing Station, 1961.* In January 1961, a serious event occurred at the National Reactor Testing Station in Idaho Falls, Idaho, involving a direct-cycle boiling water reactor of 3 MW gross thermal power. The reactor used enriched uranium fuel plates clad in aluminium, and was water moderated and cooled. After a routine shutdown for maintenance, a three-man crew was assigned the task of reassembling the control rod drives and preparing the reactor for start-up the following day. The best available evidence suggests that the central control rod was manually pulled out too fast, causing the power to rise. A subsequent steam explosion destroyed the reactor and instantly killed two men; the third man died two hours after the accident as a result of a head injury [L1].

23. *Former Soviet Union, Siberian Chemical Complex, 1961.* In August 1961, an accident occurred at the Siberian Chemical Complex in Seversk at an experimental facility used for purifying enriched (22.6%) uranium hexafluoride. The main cylinder lacked sufficient cooling, and another vessel was bypassed. The criticality alarm system was activated, and personnel evacuated the facility. Radiation surveys in the area using portable gamma monitoring instruments did not indicate abnormal radiation levels, and work resumed, resulting in a second criticality. The yield of each pulse was estimated to be 10^{16} fissions. The process operator received a dose estimated at 2 Gy and experienced mild symptoms related to ARS [L1, V1].

24. *United States, Hanford Facility, 1962.* In April 1962, an accident at a Recuplex System Process Plant in Richland, Washington, occurred as a result of the following set of conditions: cleaning the floor of a solvent extraction hood; a product receiver tank that could overflow into the hood; a temporary line running from the hood floor to a transfer tank; and the apparent improper operation of valves. A criticality excursion occurred followed by supercriticality for 37.5 hours as the power steadily decreased. The total excursion yield was 8×10^{17} fissions. Of the 22 individuals in the building, only three received significant doses of radiation ranging from 0.10 to 1.1 Gy [L1].

25. *Former Soviet Union, Arzamas-16 Nuclear Centre, 1963.* In March 1963, a criticality excursion occurred at the Arzamas-16 Nuclear Centre in Sarov in a system using plutonium with a deuteride reflector. The accident was due to the inadvertent closure of the assembly by the operator. Two individuals received doses estimated at 3.7 and 5.5 Gy. Both experienced a mild form of ARS and survived more than 25 years after the exposure. Four other persons received doses that were medically insignificant [L1].

26. *United States, Wood River Junction Chemical Process Plant, 1964.* In July 1964, an accident occurred at the Wood River Junction Chemical Process Plant in Rhode Island. The facility's function was to recover highly enriched uranium from scrap metal left over from the production of fuel elements. A variety of chemical procedures were involved in the overall process. On the day prior to the accident, a plant evaporator failed to operate properly, making it necessary to disassemble it for cleaning. During the cleaning process, a plug of uranium nitrate crystals was discovered in the connecting line. The crystals were dissolved with steam and drained into polyethylene bottles that were identical to those that normally held a very low concentration of fissile material. The bottles were labelled as high-concentration solutions. On the day of the accident the operator mistakenly poured the contents of a high-concentration bottle into the make-up vessel, which already contained 41 L of sodium carbonate solution that was being agitated by a stirrer. A critical state was reached when nearly all the uranium had been transferred. The excursion of 1.0×10^{17} to 1.1×10^{17} fissions created a flash of light and the loss of approximately 20% of the solution on to the ceiling, walls and operator. The radiation dose to the operator was estimated to be approximately 100 Gy. He died 49 hours after the exposure. Two workers who entered the room received doses of 1 and 0.6 Gy [K1, L1].

27. *Former Soviet Union, Russian Federal Nuclear Centre, 1968.* In April 1968, two technicians failed to reposition the lower reflector of an assembly prior to initiating a new test at the Russian Federal Nuclear Centre in Chelyabinsk. There was no criticality alarm system installed at the time, and health physics support was not present. The two technicians received estimated neutron/gamma doses of 5–10 and 20–40 Gy. The technician who received the higher dose died three days later, and the other technician died after 54 days [L1].

28. *Former Soviet Union, Mayak Complex, 1968.* In December 1968, a fourth event occurred at the Mayak plutonium extraction facility during a test of a new extraction process when an unusually high plutonium concentration and the presence of organic material were detected in the solution. When the solution was poured into a vessel of unsafe geometry, the operator saw a flash, the criticality alarm was activated and all personnel evacuated the facility. The shift supervisor later returned and attempted to pour some liquid into a drain, resulting in a second criticality. The first excursion yielded 10^{16} fissions and the second 10^{15} fissions. The shift supervisor died on day 34 of very severe ARS. The operator survived ARS of moderate severity, but subsequently both legs and one arm were amputated [V1, V4].

29. *Former Soviet Union, Siberian Chemical Complex, 1978.* In December 1978, another event at the complex occurred in a section of a glovebox line where plutonium metal ingots were being packed into storage boxes. The box design was deficient and it was possible to load more than one ingot into a box. A criticality excursion occurred when four ingots were loaded into a single box. The yield was 3×10^{15} fissions. One ingot was physically ejected and the operator removed the other ingots manually. The operator received a dose estimated at 2.5 Gy to the whole body and about 70 Gy to the hands; he experienced ARS of moderate severity, but amputation to above the elbows was necessary. Eyesight impairment occurred some time later. Seven other workers received doses estimated at between 0.05 and 0.6 Gy [B11, L1, V1].

30. *Russian Federation, Arzamas-16 Nuclear Centre, 1997.* In June 1997, a second criticality accident occurred at Arzamas-16 during experimental manipulation of a critical assembly. A technician was working alone in the assembly area when a component from the upper reflector slipped from his hand and fell on to the lower assembly containing the enriched uranium core. There was a flash of light, and the technician realized that a criticality had occurred. He left the experiment hall and reported the accident to his supervisors and colleagues. Initial estimates suggested a whole-body dose of 45 Gy from neutrons and 3.5 Gy from

gamma rays. The technician was promptly hospitalized. He died 66.5 hours after the exposure, despite prompt and intensive medical care [I5, L1].

2. Other accidents with only on-site consequences

31. Of the eight accidents (other than criticality accidents) in total that occurred during the operation of nuclear facilities and that led to early health effects among operators, plant staff or emergency response personnel, but had no off-site consequences for health or the environment, five occurred at facilities associated with nuclear weapons programmes and are listed in table 2a. A brief description of one of these is provided here to illustrate the nature of such events.

32. *United States, Hanford Facility, 1976.* In August 1976, a 64-year-old chemical operator was injured by a chemical explosion of an ion exchange column used for recovery of ^{241}Am at the Hanford Facility in Richland, Washington. The operator sustained chemical burns of the face, eyes, neck and right shoulder, as well as lacerations and embedded foreign bodies in these areas. He was heavily contaminated externally with ^{241}Am and inhaled an estimated 40.7 MBq of the radionuclide. Aggressive medical therapy began immediately, including on-site decontamination and administration of calcium- and zinc-DTPA. Chelation therapy continued for many months and was responsible for a significant reduction in the ^{241}Am body burden. The estimated cumulative doses three years after the accident to bone, lung and liver were 8.6, 2 and 1.6 Gy, respectively [H2].

3. Accidents with releases to the environment and potentially significant population exposures

33. Of the seven accidents at nuclear facilities that resulted in potentially significant exposures of the general public or the environment, four were associated with nuclear weapons programmes and are listed in table 2a. Three of these are described briefly below.

34. *Former Soviet Union, Mayak Complex, 1957.* In 1957, at the Mayak Complex, overheating of a storage tank containing radioactive nitrate–acetate salts led to an explosion and the release of some 740 PBq of radioactive products off-site to an area of some 20,000 km^2 of the Chelyabinsk and Sverdlovsk regions. The contaminated zone had a population of 272,000. There were 1,154 individuals inhabiting areas with a ^{90}Sr deposition density of greater than 40 MBq/m^2 [U6].

35. *United Kingdom, Windscale, 1957.* In 1957, a fire in the Windscale graphite reactor burned for three days, resulting in major releases of radioiodine and other nuclides into the environment in and around Cumbria. The release of ^{131}I was estimated at some 740 TBq. It was accompanied by 22 TBq of ^{137}Cs, 3 TBq of ^{106}Ru, 16 PBq of ^{133}Xe and 8.8 TBq of ^{210}Po. The maximum doses to local individuals were estimated to be 0.01 Gy to the thyroids of adults and 0.1 Gy to the thyroids of children. Measurements in Leeds and London indicated thyroid doses of 0.001 and 0.0004 Gy [C2, G4, U6, U9].

36. *Russian Federation, Siberian Chemical Enterprises, 1993.* In April 1993, a serious accident occurred at the Siberian Chemical Enterprises facility at Tomsk-7. The accident caused damage to both the reprocessing line and the building, resulting in the release of about 30 TBq of beta- and gamma-emitting radionuclides and about 6 GBq of ^{239}Pu. Radiological monitoring of plant personnel demonstrated that only six individuals received doses of above the 0.2 mGy detection thresholds of the dosimeters used. Dosimetry on 14 of the 20 firefighters indicated individual doses of 1–7 mGy [I19].

B. Accidents not related to nuclear weapons programmes

1. Criticality accidents

37. Of the 23 criticality accidents in total that have been reported, 6 occurred at facilities not related to nuclear weapons programmes; they are listed in table 2b and briefly described below. One of these, the 1999 accident at Tokai-mura, is also listed under accidents with releases to the environment and potentially significant population exposures.

38. *Former Yugoslavia, Boris Kidrich Institute, 1958.* In October 1958, a criticality accident occurred during an experiment at a zero power reactor facility at the Boris Kidrich Institute in Vinca. The accident exposed six individuals to relatively uniform doses of 4.36, 4.26, 4.19, 4.14, 3.23 and 2.07 Gy. One individual died as a result of the accident [L1, M4].

39. *Belgium, Venus Assembly, 1965.* In December 1965, an accident occurred at the Venus Assembly in Mol, involving a tank type water moderated (70% H_2O and 30% D^2O) critical assembly operating with 7% enriched UO_2 rods. Although there was a written rule in the reactor safety report that no manipulation of a manual rod should be performed without first emptying the vessel, a written order was given to a technician prescribing the loading of a manual control rod followed by the unloading of another one. The technician inadvertently extracted the manual rod instead of first inserting the other rod, and a criticality resulted. The technician received approximately 3–4 Gy to the head and approximately 3–10 Gy to the trunk. The dose to his feet was estimated to be 40 Gy. Medical treatment was successful, but amputation of his left foot was necessary [J3, L1, P2].

40. *Former Soviet Union, Kurchatov Institute, 1971.* In February 1971, an accident occurred at Kurchatov Institute in Moscow during a series of experiments designed to evaluate

the relative effectiveness of iron and metallic beryllium as a reflector on a power reactor core. The supervisor determined that the substitution of iron for beryllium would not result in any considerable increase in reactivity. He supervised the addition of water prior to the arrival of the console operator and supervising physicist. The control rods had not been actuated, and a criticality occurred, evidenced by a flash of blue light. The supervisor and two visiting scientists were exposed; each received a whole-body dose of about 3 Gy; the supervisor and one of the visitors received doses to the legs of between 15 and 20 Gy [L1, V4].

41. *Former Soviet Union, Kurchatov Institute, 1971.* In May 1971, a second accident occurred at Kurchatov Institute during an experimental programme to measure critical masses formed by a certain type of highly enriched (about 90%) ^{235}U fuel rod. Following the insertion of control rods and removal of the neutron source from the core, the supervisor ordered the water to be removed through a fast dump valve. Because the gap size was smaller than the size of the fast dump outlet, an internal plate sagged and fuel rods fell out of the lattice into an unsafe geometry, resulting in a criticality excursion. The yield was estimated to be 5×10^{18} fissions. Four individuals were in the facility at the time of the criticality. A technician received about 60 Gy and died five days after the accident. The supervisor received about 20 Gy and died after 15 days. The other two individuals survived doses estimated at 7–8 Gy, but suffered long-term health effects [L1, S2].

42. *Argentina, Constituyentes Atomic Centre, 1983.* In September 1983, at the Constituyentes Atomic Centre, a prompt criticality accident occurred at the RA-2 zero power critical facility light water cooled test and training reactor near Buenos Aires. RA-2 utilized 90% enriched uranium MTR-type fuel. Facility procedures required that fuel and control rod alterations be performed without the moderator present. The operator attempted to make changes to the core configuration without draining the moderator water. The core went prompt critical, resulting in the moderator expanding rapidly and shutting down the reactor. It is estimated that the operator received an initial average whole-body dose of 17 Gy due to fast neutrons and about 20 Gy due to gamma photons. He experienced symptoms of ARS, including neurological disorders, and died two days after the accident [B15, G6, L1, N1, P3, W4, W5].

43. *Japan, Tokai-mura fuel conversion plant, 1999.* In September 1999, a criticality accident occurred in a fuel conversion plant in Tokai-mura during the processing of highly enriched fuel for an experimental fast reactor. Using unauthorized procedures, the workers poured 16.6 kg of 18.8% enriched uranium into a precipitation tank, resulting in a criticality excursion. Two individuals working near the precipitation tank received whole-body doses of 10–20 Gy Eq (individual A) and 6–10 Gy Eq (individual B) from gamma rays and neutrons, using a value for the relative biological effectiveness (RBE) of 1.7. A third individual, several metres distant from the precipitation tank, received a dose estimated to be 1.2–5.5 Gy Eq. Early administration of granulocyte colony-stimulating factor (G-CSF) was used in the medical management of these individuals. Individual A died 83 days after exposure and individual B 211 days after exposure. In the course of treatment, individual A received peripheral blood stem cell transplantation from his HLA-identical sister, and individual B received a transplant of umbilical cord blood.

44. The accident resulted in off-site doses from direct neutron and gamma irradiation to nearby populations, although no significant long-term effects are expected. Approximately 200 residents living within a 350 m radius were evacuated. Ninety per cent of them received doses of less than 5 mSv. Ten per cent received doses of between 5 mSv and 25 mSv. While there were measurable levels of airborne fission products on local plant life, maximum readings were less than 0.01 mGy/h, and the activity was short-lived [A2, I6].

2. Other accidents with only on-site consequences

45. Of the eight accidents (other than criticality accidents) in total that occurred during the operation of nuclear facilities and that led to early health effects among operators, plant staff or emergency response personnel, but had no off-site consequences for public health or the environment, three occurred at facilities not associated with nuclear weapons programmes and are listed in table 2b.

3. Accidents with releases to the environment and potentially significant population exposures

46. Of the seven accidents at nuclear facilities that resulted in significant exposures of the general public or the environment, three were not associated with nuclear weapons programmes; they are listed in table 2b. Two of these are described briefly below. One other, the 1999 accident at Tokai-mura, has been listed also under "criticality accidents" and has been described briefly in subsection 1 above.

47. *United States, Three Mile Island, 1979.* In March 1979, an accident occurred at the Three Mile Island nuclear power plant near Harrisburg, Pennsylvania. The sequence of events leading to the accident began with the closure of a valve that fed water to the boiler. A series of events thereafter led to core melt and the release of fission products through a relief valve in the primary water make-up system. Most fission products were retained in the water, but about 370 PBq of noble gases, mainly ^{133}Xe, and some 550 GBq of ^{131}I were released into the atmosphere. While the accident released large amounts of activity from the failed reactor core, the resulting exposures of the public were negligible [U6, U9].

48. *Former Soviet Union, Chernobyl nuclear power plant, 1986*. The 1986 accident at the Chernobyl nuclear power plant was the most severe accident ever to have occurred in the civilian nuclear power industry. Two workers died in the immediate aftermath, and high doses of radiation to 134 plant staff and a number of emergency personnel resulted in ARS, which proved fatal for 28 of them. The accident caused the largest uncontrolled radioactive release into the environment ever recorded for any civilian operation, including 1,760 PBq ^{131}I and 86 PBq ^{137}Cs. It deposited radioactive material over large areas of the former Soviet Union and some other countries in Europe, contaminating land, water and biota, and causing serious social and economic disruption for large populations in Belarus, the Russian Federation and Ukraine. The consumption of fresh milk contaminated with ^{131}I in the first weeks after the accident led to thyroid doses that have been estimated to range between 0.05 and 5 Gy to populations of Belarus, the Russian Federation and Ukraine. More details are provided in annex D, “Health effects due to radiation from the Chernobyl accident”.

C. Summary

49. Tables 2a and 2b list 35 reported accidents at nuclear facilities that resulted in acute health effects or caused significant population exposures, of which 24 were at facilities associated with nuclear weapons programmes. In general, criticality accidents have occurred during experiments or operations in research reactors, or during work with fissile material in solution or slurries. One accident occurred in the processing of metal ingots. Only one criticality resulted in the release of radioactive material off-site, albeit a very small quantity. Of the 23 criticality accidents, 17 were at facilities associated with nuclear weapons programmes. Of the accidents at nuclear power plants, the 1986 Chernobyl accident was by far the most serious. Causes identified in these accidents were: inadequate facility design, process equipment that resulted in poor geometry, personnel errors and violation of operational procedures. Because of the regulatory regimes in place, the Committee considers it likely that most of the fatal radiation accidents at nuclear facilities have been reported.

II. ACCIDENTS AT INDUSTRIAL FACILITIES

50. Table 3 summarizes information on 80 accidents that have been reported at industrial facilities. Of these, 17 are described briefly below to illustrate the characteristics of these events. Section A presents accidents with sealed radioactive sources and section B accidents involving machine-generated radiation (i.e. from accelerators or X-ray devices).

A. Sealed radioactive sources

51. Table 3 summarizes information on 59 accidents that have been reported involving sealed radioactive sources at industrial facilities; 13 of these accidents are described briefly here.

52. *USSR, 1973*. Disregarding rules, an operator entered the main room of an industrial gamma–facility in the Moscow area, where the 4.2 PBq ^{60}Co source was unshielded. The operator walked around the source and as soon as he saw that it was in the “on” mode he immediately left the room. The estimated distance from the source to the victim ranged from 0.75 to 1 m. The whole-body dose appeared to be about 4 Gy and he survived a moderate ARS [B11].

53. *United States*, *1974*. In June 1974, at a medical product sterilization facility in New Jersey, a 61-year-old man was exposed for 5–10 seconds to gamma radiation from a 4.4 PBq ^{60}Co industrial source. The individual had failed to use a survey meter upon entering the facility and received a non-uniform exposure owing to partial shielding from Teflon-filled fibre drums. Nausea and vomiting were evident one hour after exposure, and the haematological nadir was reached about one month after exposure. The estimated dose, using cytogenetic dosimetry, was 4.1 Gy, and the patient was treated with standard antibiotic therapy and platelet/leucocyte transfusions. The individual returned to work in October 1974 [B2].

54. *United States, 1977*. In September 1977. at a facility in New Jersey, a 32-year-old man was exposed for about ten seconds to gamma radiation from an 18.5 PBq ^{60}Co source used to sterilize medical and chemical products. The accident was caused by construction work that had led to alterations in the hot cell entry area, failure to see the interlock warning and interlock failure. The individual experienced nausea and vomiting two hours after exposure. The estimated dose, using cytogenetic dosimetry, was 2.0 Gy. The patient reached the haematological nadir about 30 days after exposure and was treated with standard antibiotic therapy. Peripheral blood counts returned to normal in August 1978 [B2].

55. *United States, 1978*. In June 1978, an industrial radiographer working on a barge off the coast of Louisiana in the Gulf of Mexico sustained a radiation injury to the hand from a 3.7 TBq ^{192}Ir source. A dosimeter malfunction was thought to be the cause of the accident. About three weeks after the suspected date of exposure, the individual experienced a burning sensation, swelling, erythema and dryness of the thumb, index finger and middle finger of the left hand. The formation of bullae occurred one week later, and healing was apparent within 5–8 weeks, although the palmar surfaces demonstrated thin epithelium. Amputation of the digital two thirds of the index finger was performed at six months [S1].

56. *USSR, 1980.* An accident occurred in a gamma irradiation facility in Leningrad with a 22.2 PBq ^{60}Co source. The operator entered the irradiation room thinking the source was "down". Within less than a minute and as soon as he realized he was wrong, he left the room. However the whole-body dose appeared to be more than 12 Gy, and he died on day 10 [S2].

57. *China, 1980.* In 1980, a 25-year-old man was accidentally exposed to a ^{60}Co source in Shanghai. The estimated source activity was 1.96 PBq, and the exposure time was about 40 seconds. The individual experienced early profuse vomiting and a rapid fall in lymphocytes and other haematological parameters. The estimated dose based on the survival of haemopoietic stem cells was 5.22 Gy. Following treatment, the patient was discharged from the hospital five months after exposure. Radiation-induced cataracts were observed three years after exposure [U3, Y1].

58. *Norway, 1982*. In 1982, an accident occurred in a gamma irradiation plant at the Institute of Energy Technology at Kjeller near Oslo. The plant was used for sterilization of medical equipment. A 2.43 PBq ^{60}Co source could be raised to various positions above the shielded position on the concrete floor. Owing to technical failure and human error, the operator entered the irradiation room although the source was not in the shielded position. He stayed in the irradiation room for several minutes and shortly afterwards was found sitting outside the plant and obviously ill. Shortly after the event he was admitted to a local hospital suffering from nausea, vomiting and facial erythema. During the next four days he had persistent nausea and increasing mucositis in the mouth. After a week his haematological values were markedly reduced. On the basis of dose reconstruction using electron spin resonance (ESR) spectroscopy of nitroglycerine tablets in his pocket, the mean whole-body dose was considered to have been slightly above 20 Gy. The patient died 13 days after exposure [R1, S3].

59. *China, 1986.* In May 1986, in Kaifun, Honan Province, a young man and a young woman were accidentally exposed to a 255 TBq ^{60}Co source for about 1.5–2 minutes at a local irradiation facility. The man received a whole-body dose estimated at 3.5 Gy and the woman a dose estimated at 2.6 Gy. Both individuals experienced radiation-induced vomiting and haematological depression [W2, Y1].

60. *China, 1987.* In March 1987, in Zhengzhou, Honan Province, a young man was exposed for 10–15 seconds to photons from a ^{60}Co source of 3.29 PBq. The estimated exposure was 1.35–1.45 Gy. He experienced lassitude, thirst and dryness of the eyes immediately after exposure. Four hours later he experienced nausea and anorexia but no vomiting. The nadir values of leucocytes and platelets occurred on the 35th and 31st days, respectively. Restoration of his leucocyte count was rather slow, and the count remained subnormal until the 120th day after exposure [Y1].

61. *El Salvador, 1989.* An accident occurred in February 1989 at an industrial irradiation facility near San Salvador. The facility had 0.66 PBq of ^{60}Co in a movable source rack, badly degraded safety systems and poor maintenance at the time of the accident. After the unshielded source rack became stuck, three individuals entered the radiation room and received non-uniform doses to the whole body. Subsequently they all developed ARS. Cytogenetic studies indicated doses of 8 Gy to patient A, 3.6 Gy to patient B and 3 Gy to patient C. Two of these individuals experienced serious radiation-induced injuries of the lower extremities, with doses estimated at 100 Gy. They were transferred to a specialized hospital in Mexico City. The leg of the most seriously irradiated individual was amputated approximately four months after exposure. Following transfer back to El Salvador, this patient died as a result of a surgical procedure and complications due to radiation-induced lung damage. Another individual required amputation of both legs. A third individual experienced minor injuries to one foot. Before the accident was fully understood, a fourth individual, a maintenance manager, entered the facility and received a whole-body dose that was medically insignificant [I1].

62. *Israel, 1990.* In June 1990, at a commercial irradiation facility in Soreq, an operator bypassed safety systems to enter the irradiation room in order to free cartons stuck on the conveyor system. He was not aware that the movable ^{60}Co source rack was obstructed in the irradiation position. At the time of the accident the total activity was 12.6 PBq. He promptly developed symptoms and left the area. It was determined that his whole-body dose was between 10 and 20 Gy. He was hospitalized with severe haematopoietic and gastrointestinal syndromes, and skin injury was soon evident. Despite aggressive medical efforts, including use of haematopoietic growth factors and a bone marrow transplant, he died 36 days after exposure [I2].

63. *China, 1990.* In June 1990, seven workers were exposed to radiation from a ^{60}Co source at an industrial facility in Shanghai. The accident was caused by improper maintenance of safety features. None of the workers was wearing a personal dosimeter at the time of the accident. One individual, with a dose estimated at 12 Gy, died 25 days after exposure. A second individual, whose dose was estimated at 11 Gy, died 90 days after exposure. The other five workers received doses estimated to range from 2 to 5.2 Gy and recovered after medical treatment [L2, P1].

64. *Belarus, 1991.* In October 1991, an accident occurred at a ^{60}Co irradiation facility used to sterilize agricultural and medical products in the town of Nesvizh. The source activity was 28.1 PBq at the time of the accident. Owing to a malfunction of the product transport system and human error, the operator entered the irradiation area and remained inside for 1–2 minutes with the source array in the full "out" position. He received prompt medical attention in Belarus and then in Moscow. He experienced ARS and skin injuries resulting from an estimated whole-body dose of 11–18 Gy. His intensive medical treatment included administration of

granulocyte–macrophage colony-stimulating factor (GM-CSF). He died 113 days after exposure of pulmonary and multiorgan failure [I3].

B. Accelerators and X-ray devices

65. Table 3 summarizes 21 accidents involving machine-generated radiation (i.e. from accelerators or X-ray devices), four of which are described briefly here.

66. *United States, 1960.* In March 1960 nine civilian employees at a military installation in Lockport, New York, were exposed to X-radiation from an unshielded klystron tube. Two of the individuals were seriously injured, five other individuals demonstrated less severe injuries and two individuals remained asymptomatic. The highest dose received was estimated to be 12–15 Gy (non-uniform). Seven exposed individuals demonstrated varying degrees of nausea, vomiting, headache, erythema, fatigue, epilation and conjunctival reddening. The individual with the highest estimated dose demonstrated signs and symptoms of ARS [H5].

67. *United States, 1967.* In October 1967 three technicians in Pittsburgh, Pennsylvania, simultaneously incurred accidental non-uniform whole-body exposures to radiation from a water-cooled Van de Graaff linear accelerator. The water cooling system had failed, and the technicians were attempting to repair the system. They followed all safety procedures and entered the accelerator area unaware that the safety interlock system had failed. The workers experienced early signs and symptoms of radiation injury, and dosimetric tests indicated whole-body exposures of 1, 3 and 6 Gy. The most seriously irradiated worker also had localized doses of 59 Gy to the hands and 27 Gy to the feet. He had a more complicated clinical course, and demonstrated pancytopenia and complete bone marrow depletion. His situation was unique because he had an identical twin brother who donated bone marrow for transplant on the eighth day after exposure. The patient developed extensive local skin injury to the hands and feet, and four months after exposure, amputation of portions of the hands and feet was performed. The amputation sites manifested lack of healing, and further necrosis led to 11 additional operative procedures over a 22 month period. The patient was eventually fitted with prostheses on all extremities. He required psychological support for many years [G2, G3].

68. *France, 1991.* In July and August 1991, three individuals working at an accelerator facility in Forbach received high doses of radiation from a Van de Graaff device. The accident was reportedly due to negligence and non-compliance with regulatory requirements. The workers' exposure was associated with "dark current" after the accelerator had been turned off, although the voltage was maintained to save time. The residual dose rate was a few grays per second. The most severely exposed individual suffered skin lesions following a dose estimated at 40 Gy, while the other two were less seriously affected [C1, U3, Z3].

69. *United States, 1991.* In 1991, an accelerator operator at a facility near Baltimore, Maryland, was exposed to electron dark current during routine maintenance. The filament voltage was off, but the high voltage was on, resulting in dose rates of 0.4–13 Gy/s. The operator placed his hands, head and feet in the beam. Three months later, most of the digits on both of the operator's hands had to be amputated. Using electron paramagnetic resonance (EPR) on bone samples from the fingers, the dose was estimated to be 55 Gy [D3].

C. Summary

70. Table 3 lists 80 accidents at industrial facilities. Nine deaths were reported in these accidents. They all occurred at industrial irradiation facilities using high-activity sealed sources, primarily because of improper entry into the hot cell, and a lack or failure of safety mechanisms. At least 84 other people were excessively overexposed in these facilities. In other industries, 36 workers were injured during the use of radiography sources, X-ray devices and accelerators, and during manufacturing procedures. The Committee considers it probable that some accidents at industrial facilities involving deaths and injuries have not been reported.

III. ACCIDENTS INVOLVING ORPHAN SOURCES

71. Orphan sources are radioactive sources that were never under regulatory control or were under regulatory control but then abandoned, lost, misplaced, stolen or otherwise transferred without authorization [G1]. Orphan sources have been the cause of serious accidents involving members of the general public, who were entirely unaware that they were being exposed to radiation. Table 4 summarizes key information about 34 accidents involving orphan sources (sometimes multiple sources). Of these, 20 are described briefly below to illustrate some of the characteristics of these events.

72. *Mexico, 1962.* Between March and September 1962, an engineer left a 200 GBq ^{60}Co source unprotected in the yard of a house in Mexico City. The source was found by a 10-year-old boy and subsequently taken to his home, where it remained for approximately four months. The boy and his sister died following estimated protracted whole-body doses of 47 and 28.7 Gy, respectively. The children's mother and grandmother also died following doses estimated at 35 and 30 Gy, respectively. The children's father survived, although he became permanently sterile, following an estimated protracted dose of 120 Gy [M6].

73. *China, 1963.* In 1963, a ^{60}Co source with an estimated activity of 0.43 TBq was found in a lead cask by a farmer fishing near the Anhui Agricultural Institute, located in Hefei City in Anhui Province. He took the source and returned to his home. Nine days later, authorities located the source. The six individuals living in the home were sent to a hospital for medical assistance. Two individuals in the home received estimated whole-body doses of 80 Gy and 40 Gy, and died within the following two weeks. The other four individuals received doses estimated at 8, 6, 4 and 2 Gy, and survived after medical treatment. No significant long-term effects were noted 17 years after exposure [P1].

74. *Mexico, 1973.* On 24 May 1973, during the construction of the refinery at Tula, in Hidalgo state, a truck was transporting a container holding a ^{137}Cs source. The container had a "plug" made of a piece of wood. Owing to the motion of the truck, the plug failed and allowed the source to emerge from the container. The box that held the container had a crack, and the source fell out on to the road. A 38-year-old bricklayer found it and took it home, carrying the source in his trouser pocket for several hours. The dose to the thigh was reported to be 1,386 Gy. He subsequently suffered radiodermatitis of the left thigh median third and the buttock. His left leg was amputated from the hip down; the middle finger of the right hand was also amputated. His family, who were exposed to the source over three days, showed no symptoms of radiation injury [N5].

75. *Algeria, 1978.* In May 1978, a 925 GBq ^{192}Ir source used for industrial radiography fell from a truck travelling on the road from Algiers to Setif. Two young boys found the source a few days later. Both boys handled the source, and it was eventually placed in their home. It remained there for 5–6 weeks, exposing the family to radiation under various conditions depending on their location and time spent in the kitchen. The two boys developed serious skin lesions; their 47-year-old grandmother and four females aged 14, 17, 19 and 20 years, who spent most of their time in the house, were exposed to varying doses. The actual doses to these five females were difficult to resolve, owing to many uncertainties, including those in the total time of exposure per day, geometry, shielding and distance from the source over a period of 38 days. Thus their treatment was based primarily on haematological presentations. The grandmother died in late June 1978. The foetus of the pregnant 20-year-old woman also died during the haematological recovery period of the mother, and both boys required surgery for their skin injuries [J2].

76. *United States, 1979.* In June 1979 a worker at an industrial site in Los Angeles (Riverside), California, found a lost ^{192}Ir radiography source with an estimated activity of 1.04–1.22 TBq. The worker placed the source in his right hip pocket and left it there for approximately 45 minutes. He subsequently developed a severe ulcerated radiation burn. The estimated skin surface dose was 800–4,000 Gy, and the 1 cm tissue depth dose was 520 Gy to an area measuring 11 × 9 × 2 cm. At 36 days after exposure a full-thickness myocutaneous flap, with vascular pedicle intact, was mobilized from the right thigh and sutured to the bed of the excised ulcer. Additional surgeries were required since the lesion did not completely heal. Five other workers handled the source before it was returned to the radiographer. Four of these workers developed moderate injuries to the fingertips. An additional five workers did not have medically significant exposures [H8, R2].

77. *Mexico, 1983.* In early December 1983, a ^{60}Co therapy machine was dismantled and loaded into a pick-up truck. The machine had been acquired in November 1977 by the Centro Medico Hospital in Ciudad Juarez and had been in storage since its acquisition. The source activity was about 16.6 TBq contained in some 6,000 small pellets, each with an average activity of 2.77 GBq. During the dismantling, the source container was punctured and a number of pellets (800–1,000), with an estimated activity of 1.85 TBq, were spilled into the truck's cargo area. The truck was later parked on a city street and was not discovered for about seven weeks. The machine was sold at a local scrapyard and then to foundries in Chihuahua and Durango, Mexico, with subsequent contamination of metal. During movement of the machine, some cobalt pellets were lost on the streets of Ciudad Juarez, in the scrapyard, along highways and in the foundries.

78. The accident was not discovered until January 1984 when a truck loaded with contaminated rebar stopped at an entrance to the Los Alamos National Laboratory in New Mexico, United States, and tripped radiation alarms. An investigation led to the discovery of the pick-up truck. No acute effects were noted in the general population; doses were protracted over a period of about 60 days. Cytogenetic dosimetry was performed on two scrapyard employees and eight individuals living near where the truck had been parked. Owing to uncertainties regarding exposures of the individuals, two mathematical models were used to estimate doses. The mathematical model used to extrapolate dose assuming acute exposure at a high dose rate resulted in estimates of 0.09–1.91 Gy. The estimate assuming chronic exposure at a low dose rate ranged from 0.13 to 15.16 Gy. There were no fatalities reported following the accident [B3].

79. *Morocco, 1984.* In March 1984, a worker at a facility in Casablanca took home an industrial radiography source (603 GBq of ^{192}Ir) and placed it on a shelf near his bed. The worker died 44 days after exposure. Over the next several weeks, the worker's pregnant wife and their four children also died as a result of their exposures. After the father's death, a cousin and his mother stayed in the house, using the room where the source was located. These two individuals also died as a result of their exposures. Three other persons living in the house experienced bone marrow suppression but survived their overexposures. Authorities recovered the source 80 days after it was removed from the facility [M2, M5].

80. *China, 1985.* In April 1985, an accident occurred in Mudanjiang when a lost source (370 GBq of ^{137}Cs) was brought into a dwelling where a 21-year-old man and his

parents (the mother was 68 years old and the father 66 years old) were exposed over a period of 150 days with estimated cumulative whole-body doses of 8–10 Gy to each individual. The father also experienced a radiation-induced burn on his right thigh. The clinical findings upon hospital admission were general malaise, bleeding and pancytopenia. The therapeutic measures were bed rest, adequate nutrition and strict control of infection. The father died from myelodysplastic syndrome complicated by pulmonary fungal infection 22 months after exposure. The other two individuals remained apparently well [Y1].

81. *Brazil, 1987.* In 1987, an abandoned 50.9 TBq ^{137}Cs teletherapy device located in Goiânia was stolen and dismantled, and the source capsule ruptured. Over the next two weeks, ^{137}Cs chloride powder was spread throughout a scrapyard, surrounding homes and the vicinity. The problem of radiation exposure was noted after numerous individuals developed illness and skin lesions. Subsequently a monitoring station was set up at a soccer stadium and 110,000 persons were monitored for contamination with radioactive material. Of these individuals, 249 were found to have ^{137}Cs deposits on their skin or clothing, and 129 of these persons were found to be internally contaminated with ^{137}Cs. Outpatient care was provided to 79 individuals, while 50 required close medical surveillance. Of these latter patients, 14 required intensive medical care for ARS, internal contamination and local lesions. Four persons died, including one child. There are 150 persons currently in a follow-up cohort. A group of 755 professionals participated in extensive environmental decontamination. Eighty-five residences required decontamination, and seven residences had to be demolished. The total volume of waste generated for temporary storage amounted to 3,134.5 m^3 and since 1987 has been disposed in a repository [I11, I12, N8].

82. *USSR, Ukraine, 1988–1991.* This accident occurred when a family consisting of a man, a woman and two children moved to an apartment in a new complex built 200 km south-east of Kiev. After several months the older son became ill and was found to have bone marrow depression. The cause was not identified, and the boy recovered and returned home. Over the next year the same scenario was repeated several times, and the boy developed osteosarcoma of the foot and died of metastatic disease. His younger brother was then allowed to move into his bedroom, and within several months developed severe bone marrow depression. The younger boy also developed a necrotic lesion on his foot. Thinking the problem was associated with the Chernobyl accident, the boys' mother requested authorities to survey the apartment for radiation. Finally a 2.6 TBq ^{137}Cs industrial source was found embedded in the wall of the boys' bedroom, located near the foot of the bed. How the source came to be there was never clear. Several months later the younger boy developed additional haematological problems and subsequently died [M2, S2].

83. *China, 1992.* In November 1992, in Xinzhou, Shanxi Province, a farmer was demolishing a closed irradiation facility when he found a 100 GBq ^{60}Co source contained in a cylindrical steel bar. The individual placed the bar in his jacket. Later that afternoon he was sent to a local hospital after complaining of nausea followed by vomiting. The jacket containing the source remained with the individual during his hospitalization. He died in early December. His father and elder brother, who had taken care of him at the hospital, died from exposure the following week. The farmer's wife also assisted in his care, and in mid-December she requested medical assistance. The doctors suspected that she, too, was suffering from radiation exposure. Through dose reconstruction, the farmer, his father and his brother were estimated to have received doses of greater than 8 Gy, and the dose to his wife was estimated to be about 2.3 Gy [P1].

84. *Turkey, 1993–1998.* Unauthorized long-term storage (1993–1998) and subsequent transport and transfer to a new owner resulted in a loss of control over two ^{60}Co therapy sources in Istanbul. The packages containing the sources were sold as scrap. Later the shielding of one container was opened at the scrapyard. In December 1998 ten persons fell ill, and six experienced nausea and vomiting. The cause of their illness was not diagnosed until four weeks later. Once the cause had been diagnosed, media reports caused alarm, and 404 persons applied for medical examinations. Eighteen persons (including seven children) were admitted to hospital. Ten of the hospitalized adults exhibited signs and symptoms of ARS. Five of these persons were hospitalized for 45 days. One person had local injury to a finger [I7].

85. *Estonia, 1994.* In October 1994 in Tammiku, three brothers entered a waste repository without authorization and removed a metal container holding a 1.6 TBq ^{137}Cs source. During removal the source was dislodged and fell to the ground. One of the men picked it up and placed it in his pocket. Before leaving the repository, he began to feel ill. A few hours later he began to vomit. He took the source to his home in the nearby village of Kiisa. Subsequently he was admitted to a hospital with severe injuries to his leg and hip, and he died on 2 November 1994.

86. The injury and subsequent death were not initially attributed to radiation exposure, and the source remained in the man's house with his wife, his stepson and the boy's great-grandmother. The boy was hospitalized on 17 November with severe burns on his hands, and a doctor identified the burns as being induced by radiation. The authorities were alerted, and the Estonia Rescue Board recovered the source from the house. The occupants of the house and one of the man's two brothers were hospitalized and diagnosed as suffering from radiation-induced injuries of varying severity. All were subsequently released from the hospital and continued to receive outpatient treatment for at least four years. Studies conducted on other people living in the area where the source was discovered revealed no symptoms of radiation sickness [I13].

87. *Russian Federation, 1995.* In 1995, a 48 GBq ^{137}Cs source was discovered in the cabin door pocket on the

driver's side of a truck near Moscow. The driver of the truck was apparently overexposed over a period of about five months. The dose rate at the left side of the driver's seat was estimated to be about 50 mGy/h. An estimate of the average whole-body dose of 7.9 ± 1.3 Gy was made on the basis of cytogenetic studies of chromosomal aberrations in the driver's blood lymphocytes. The driver was hospitalized in Moscow in July 1995 with complaints of fatigue and shortness of breath. Epilation was evident on the lateral surfaces of the left thigh and buttock. Pancytopenia, myelodysplasia and anaemia progressed over the next several months, eventually leading to myelomonocytic leukaemia. The individual died 22 months after the source was discovered [B7, S7].

88. *Islamic Republic of Iran, 1996.* In July 1996, industrial radiography was under way at the Gilan combined cycle fossil fuel power plant located 600 km north of Tehran. After making a series of radiographs, the radiography team failed to notice that the 185 GBq ^{192}Ir source was missing from the container. A 33-year-old plant employee found the source, handled it and then placed it in his shirt pocket, where it remained for about 90 minutes. Over the next few weeks the irradiated individual demonstrated haematological depression and was treated with antibiotics, platelet transfusions, and the haematological growth factor granulocyte-colony-stimulating factor (G-CSF). He also developed lesions to the right thorax, right elbow, right thigh and left palmar surface. He was treated in Tehran and subsequently transferred to Paris for treatment of his skin lesions. His chest and thigh lesions were successfully treated with a free graft from the undamaged thigh. About 16 months after exposure, the skin lesions healed, although there was thickening of the skin on the hand, slight retraction on the right side due to the fibrotic chest graft and contracture of the right elbow. The estimated whole-body dose was 2–4 Gy, while the maximum skin doses did not exceed about 40 Gy [I21].

89. *Georgia, 1996–1997.* Numerous sources were abandoned when Soviet troops turned over the Lilo Training Centre to the Georgian army in 1992. From April to August 1997, several Georgian soldiers sought medical care because of skin lesions. After radiation injury was diagnosed, high-activity sources were found 30 cm below the surface of a soccer field, 10 cm below ground in an area used for smoking, stored in lead containers and in the pocket of a soldier's winter jacket. In addition, 200 discarded sighting devices containing ^{226}Ra and a ^{60}Co source were found. In total, 12 ^{137}Cs sources were located. Eleven persons suffered local and systemic effects as a result of their exposures. The estimated doses for protracted exposures ranged from 4.2 to 0.6 Gy. Seven patients remained under treatment in 1999 [I20].

90. *Peru, 1999.* In February 1999, an ^{192}Ir industrial radiography source with an estimated activity of 1.37 TBq was lost at the Yanango hydroelectric power plant in the San Ramon district 300 km east of Lima. A few hours later a welder found the source and placed it in the right back pocket of his trousers. Over the next several hours the welder worked in a pipe and then took a minibus home. He changed clothing, placing his trousers (with the source still in the pocket) on the floor, and sought local medical assistance because of pain in his right thigh. He was diagnosed with an insect bite. Meanwhile his wife sat on the trousers while breastfeeding her 18-month-old child. Authorities recovered the source at 1 a.m. the following morning, and the welder was transferred to Lima for medical care. The estimated 1 cm depth dose to his thigh was 9,966 Gy, and over the next three months he developed an extensive severe lesion on the right thigh. He was then transferred to Paris for skin grafts using porcine xenografts. The grafts failed, and the right leg was disarticulated at the hip. Additional surgeries were required after the welder's return to Peru. His wife developed moist desquamation and ulcerative and fibrotic lesions of her lower back [I8].

91. *Thailand, 2000.* In 1999, unauthorized teletherapy sources were relocated to an unsecured site in Samut Prakarn. In January 2000, four scrap collectors gained access to the facility, partially disassembled a teletherapy head and took the device home for further disassembly. On 1 February two of the individuals sold the components to a junk dealer. During further disassembly of the device at the junkyard, the source fell out of its housing but was not noticed. By mid-February several individuals had sought medical attention, and suspicion of radiation injury was reported to the authorities. The 15.7 TBq ^{60}Co source was recovered on 20 February. Ten people were hospitalized. Three junkyard employees died of ARS-associated infections in March. Four other individuals suffered local injuries; one required hand amputation. G-CSF and GM-CSF were used in the medical management of these patients [I9].

92. *Egypt, 2000.* In May 2000, a farmer from Meet Halfa village found a 1.17 TBq ^{192}Ir industrial gamma radiography source that had been lost by a worker testing pipe welds. The farmer took the source to his home, where he lived with his wife, a sister and four children. In the following weeks the source was handled by family members and moved to various locations within the family home. The 9-year-old son died in June, and death was reported to be due to bone marrow failure and inflammation caused by a viral or bacterial infection. Other family members were also found to be sick with skin lesions, bone marrow failure and gastrointestinal symptoms, but the diagnosis again was incorrect. On 16 June the farmer died. On 25 June, a fact-finding mission detected high radiation levels at the family home, and the source was recovered. Family members were hospitalized with skin lesions and bone marrow depression. G-CSF was used in their treatment. Dose estimates were: father, 7.5–8 Gy; 9-year-old son, 5–6 Gy; five other family members, 3.5–4 Gy. Between 200 and 300 neighbours and relatives were monitored, and the affected family received continuing treatment and surveillance [E1, I10].

93. *Georgia, 2001.* In December 2001, three woodsmen found two heat-emanating ceramic objects near their

campsite in the remote Inguri River Valley of Georgia. Two of the woodsmen carried the containers on their backs, and experienced nausea, vomiting and dizziness within hours of exposure. The third carried the source attached to a wire. At a hospital in Tbilisi, the woodsmen were diagnosed with radiation sickness and severe radiation burns, and at least two of the three men were in serious condition. A Georgian team recovered the sources in early 2002 with the assistance of the International Atomic Energy Agency (IAEA). They were unshielded ceramic sources from two Soviet-era radioisotope thermoelectric generators (RTGs), each containing about 30,000 Ci (1 PBq) of ^{90}Sr. Two of the patients were treated in hospitals in Paris and Moscow for many months before recovering from their severe radiation burns [I23].

A. Summary

94. Table 4 presents information on 34 accidents involving orphan sources. These accidents resulted in 42 early deaths and in disfiguring injuries to both children and adults. Significant environmental contamination and the internal contamination of 129 persons occurred in one of these accidents. The Committee considers it probable that some radiation accidents involving orphan sources and that resulted in deaths or injuries have not been reported.

IV. ACCIDENTS AT ACADEMIC AND RESEARCH FACILITIES

95. Table 5 summarizes information about 22 radiation accidents at academic and research facilities, seven involving sealed radioactive sources and 15 involving machine-generated radiation (i.e. from accelerators and X-ray devices). Some examples of these accidents are described briefly below to illustrate the nature of these events.

A. Sealed radioactive sources

96. *USSR, 1962*. A ^{60}Co source of about 1.9 PBq was used at a research institute in Moscow for irradiating metal samples. A researcher opened the locked door and entered the irradiation room, believing the time to change the sample would be so short as to be not dangerous. However, she received a whole-body dose (non-uniform) of about 2.5–3.0 Gy, and 12 Gy to her right hand. She survived a moderate ARS with mild local skin injury [G5].

97. *United States, 1971.* In February 1971, a 32-year-old technician was performing seed irradiation experiments at the Variable Dose Rate Irradiation Facility at the University of Tennessee Comparative Animal Research Facility in Oak Ridge. Because of an interlock failure, the technician was able to enter the facility with a 285 TBq ^{60}Co source unshielded. He was within 50 cm in front of an unshielded source for about 40 seconds. When the technician left the facility, the operator noticed that the source was unshielded and notified the authorities. The technician was hospitalized within two hours, and experienced episodes of nausea and vomiting starting 2.25 hours after exposure and lasting for about 24 hours. Maximum haematological depression lasted from day 24 to day 34 after exposure. The estimated whole-body and bone marrow doses were 1.27 Gy and 1.18 Gy. The patient was treated with standard antibiotic and haematological support, and returned to work 11 weeks after exposure [V2].

B. Accelerators and X-ray devices

98. *USSR, 1977.* In March 1977, a 40 MeV proton accelerator in the Institute of Nuclear Physics, Kiev, was activated for the first time. A physicist—who had fostered its construction—decided to demonstrate the presence of the beam. He inserted a luminescent lamp by hand “into the beam”, and it illuminated. However the physicist received an absorbed dose within the hands’ tissues ranging from 12 Gy on the surface to more than 30 Gy at the depth of 0.5 cm at some points. This led to a complicated clinical course of local radiation injury to both hands, and several surgical interventions were performed in order to save some of the hands’ functionalities [A5, B12].

99. *United States, 1977.* In April 1977, a graduate student at the Donner Laboratory of Lawrence Berkeley Laboratory, University of California at Berkeley, was conducting a research experiment involving the effects of X-rays (about 30 kVp) on yeast cultures. On the day of the accident the student was to expose 60 Petri dishes of yeast cultures. An interlock failure resulted in the student’s hands receiving about 70 Gy. There was noticeable erythema within 12 hours, followed by blistering and desquamation over a period of several months. Two fingers on the left hand and one finger on the right hand were amputated [T2, U3].

100. *USSR, 1978*. A powerful 70 GeV proton accelerator was used at the Institute of High Energy Physics, Protvino, for a broad spectrum of scientific experiments. In June 1978, after a long chain of procedure violations and errors, a researcher was accidentally exposed to a needle-thin beam of protons, which pierced his head from left occipital lobe of the brain to the left nostril. His middle ear was destroyed, and facial nerve injured. He survived, and the function of the facial nerve was restored. However, deafness in his left ear and a scar on the left nostril remained; and brain damage caused mild epilepsy six years later [B13].

101. *USSR, 1978*. An accident occurred in an electron linear accelerator in Leningrad, involving a 12.7 MeV electron beam. A worker entered the experimental room after irradiation was complete and a timer had cut the voltage to the controlling electrode. She stood with her back to the exit window and then turned 180°. It appeared that she was exposed twice owing to so-called "dark current", because the high voltage to the accelerating tube was still on. The localized doses to her back and chest were estimated as more than 20 Gy and 8 Gy respectively. Skin reactions corresponded to these doses; however, signs of severe radiation damage to the spinal cord appeared six months later [A5].

102. *Vietnam, 1992*. In November 1992, an accident involving a research X-ray accelerator occurred at the Hanoi Institute of Health Physics. One individual entered the irradiation room without supervision and subsequently exposed his hands to the X-ray beam. The dose to the individual's left hand was estimated to be 10–25 Gy, and the whole-body dose was estimated to be 1–2 Gy. The individual's hands were seriously injured, and one hand had to be amputated [I4].

103. *United States, 1994*. In June 1994 two graduate students at the University of California at Davis were analysing samples using a water-cooled Enraf-Nonius X-ray diffraction unit operating at 45 kVp, 25 mA, with the timer mode set in the "continuous" position. On previous occasions, the students and a faculty member had dismantled the unit to clean corrosion that had built up between the X-ray tube column and the primary shutter. Procedures called for the unit's electrical power to be in the "off" position. The students had, however, adopted the practice of expediting sample changing by bypassing the cabinet door safety interlock rather than turning the power to the "off" position. This led to significant exposure to areas of both hands of one of the students. The skin entrance dose rate was 960 Gy/min. The clinical course over one year after exposure included tightness and paraesthesiae in the student's fingers, swelling, erythema, bullae, hyperkeratosis and significant pain [B4].

C. Summary

104. Table 5 lists accidents in academic and research facilities. Twenty-two accidents have been reported in the use of accelerators, research reactors, radiochemistry laboratories, small irradiation facilities, and with the use of X-ray diffraction, spectroscopy, crystallography and fluorescence units. The hands were commonly the area injured. The Committee considers it probable that some radiation accidents in academic and research work have not been reported.

V. ACCIDENTS ASSOCIATED WITH THE MEDICAL USE OF RADIATION

105. A summary of nearly 100 radiotherapy accidents has been presented by the IAEA [I25], and a similar number have been reported by the International Commission on Radiological Protection (ICRP) [I24]. Table 6 summarizes information on 32 serious radiation accidents associated with the medical use of radiation. Some examples of accidents associated with the diagnostic and therapeutic uses of radioactive materials and machine-generated ionizing radiation are described briefly below. More discussion on accidents in radiotherapy is provided in annex A, "Medical radiation exposures".

A. Nuclear medicine

106. *United States, 1968*. In August 1968 a 73-year-old woman was scheduled for a diagnostic nuclear medicine liver/spleen scan at a hospital in Wisconsin. The radiopharmaceutical being used was colloidal ^{198}Au, administered intravenously. The intended activity was 7.4 MBq, but because of an error, the patient received 1,000 times more of the radionuclide, or 7.4 GBq. The estimated bone marrow dose was 4–5 Gy, and the dose to the liver was 70–90 Gy. The patient died 69 days after exposure [M3].

B. Sealed radioactive sources

107. *United States, 1974–1976*. This accident involved 426 patients being treated with a ^{60}Co teletherapy unit over a 16-month period (1974–1976) at the Riverside Hospital in Columbus, Ohio. Dose rates had been underestimated by 10–45% owing to an error in calculating the source decay and to a lack of routine periodic calibration. Of the 183 who survived beyond one year, 34% had severe complications, some of which led to death. Fifteen years after the accident, 18 individuals remained alive, with 50% experiencing severe complications [M1].

108. *France, 1981*. During the initial loading of a radiation therapy device in a new radiotherapy department in Saintes, the 137 TBq ^{60}Co source had become jammed in the loading channel instead of being in its retracted, shielded position. Unaware of this, an assistant operator placed his hands in contact with the device in an area where the source was jammed. On removal of the source transport apparatus that contained a dummy source, both the dummy source and the ^{60}Co source fell on to the floor. Despite 25 years of experience, the main operator picked up the source with his bare hands and put it in a safe position. Doses to the hands

of both the operator and his assistant exceeded 25 Gy at the wrists. The amputations of both hands of both victims were unavoidable. A third operator received an unexplained high-level exposure of one hand, leading to amputation of a large portion of the hand [N7].

109. *United States, 1992*. An accident occurred in November 1992 in Indiana, Pennsylvania, involving a female patient scheduled for a high-dose-rate brachytherapy procedure using a 159 GBq ^{192}Ir source. The treatment was to be given in three fractions of 6 Gy each. During the first procedure the source broke off the guide wire and remained inside one of the catheters surgically implanted into the patient's tumour. A radiological survey of the patient was not performed, and she was returned to a local nursing home. The source became dislodged from the catheter on day 4 and was discarded in the biohazard waste. It was discovered some days later when a waste truck passed through a radiation detector installed at an incinerator facility.

110. The estimated dose at 1 cm in tissue was 16,000 Gy. Death occurred four days after the procedure, but was thought to be associated with the patient's disease and age. The patient's remains were later exhumed and an autopsy was performed, resulting in the death certificate being changed to reflect death from ARS. Ninety-four additional individuals, including staff, visitors, family members and other nursing home residents, were exposed, although the doses were not medically significant [N4].

111. *Costa Rica, 1996*. In August 1996, a ^{60}Co radiotherapy source was replaced at a hospital in San José. Following the replacement, a calibration error was made. Over the next 37 days, radiation doses 50–60% greater than those prescribed were delivered to 115 patients under treatment for neoplasms. These overexposures were confirmed by recalibration of the source and review of individual patient charts. In July 1997, an IAEA investigation team evaluated 70 of the 73 patients who were still living. The team concluded that 20 patients were suffering from major adverse effects due to their overexposures, with 26 other patients experiencing less severe effects. Twenty-two had no discernible effects, because of incomplete therapy. Two patients were underexposed and three were not examined. Seventeen deaths associated with the radiation exposures were reported [I14, I24].

112. *Panama, 2000.* At the Instituto Oncológico Nacional in Panama, a computerized treatment planning system was used to calculate the dose distribution and determine treatment times. In August 2000, medical physicists changed the method for entering data on shielding blocks in the computer program in order to overcome limitations for treatments that required more than four blocks. Soon thereafter, the radiation oncologists started to observe prolonged diarrhoea in some patients. In March 2001, physicists identified a problem with the calculation of exposure times, and the treatment of patients with abnormal symptoms was suspended. Further studies revealed that 28 patients had received a proportionately higher dose than prescribed. Further investigations were undertaken, although eight patients had already died. At least five of these deaths were probably radiation related. The 20 surviving patients were examined, and a number were found to be suffering from bloody diarrhoea, necrosis, ulceration and anaemia [B10, I15].

C. Accelerators and X-ray devices

113. *United States and Canada, 1985–1987.* In 1985, 1986 and 1987, several serious overexposures occurred when patients were being treated for carcinoma using a Therac-25 electron linear accelerator. The device was first manufactured in 1982, and 12 units were in use within the United States and Canada. Accidents occurred in United States hospitals located in Marietta, Georgia; Tyler, Texas; and Yakima, Washington; as well as at a hospital in Hamilton, Ontario, Canada. Control of the device was achieved using a small digital computer. Unfortunately, the computer had a software problem such that when the technician made an error in the treatment procedure, the computer screen displayed a "malfunction 54", which was the code for "dose input error". This resulted in the patient receiving a direct electron beam at 25 MeV.

114. Six patients were irradiated during machine malfunction and received severe burns. Two of the patients died as a result of their injuries following therapy in Texas. In March 1986, a 33-year-old man with a liposarcoma on his left upper back was treated; owing to the machine malfunction, the patient experienced severe damage to the cervical cord, resulting in death five months after exposure. In April 1986, a 66-year-old man with a multifocal skin cancer on the left side of the face was treated during machine malfunction. He died three weeks later from damage to the right temporal lobe of the brain and the brain stem [N2].

115. *Spain, 1990.* In Zaragoza, 27 patients received higher radiotherapy doses than those prescribed, because of a malfunction in a linear accelerator. During a repair procedure, the electron energy of the accelerator was modified, and this change was not noted by the therapists, who thought that the meter on the control panel was faulty. The increased energy resulted in greater penetration of energy and effects on deeper tissues. In addition, the electrons were focused in a smaller cross-section of the beam. This resulted in doses three to seven times higher than intended. Patients developed injuries in the lungs, pharynx and spinal cord, complicated by vascular and skin injuries. As the victims of this malfunction were suffering severe tumours for which they were being treated with radiation, it is difficult to accurately assess the contribution of the accident to the number of deceased. It was estimated that 15 patients died with radiation as the primary or major cause of death, while others had severe disabilities [I24, S5].

116. *Poland, 2001.* In February 2001, at the Bialystok Oncology Centre, a serious accidental overexposure injured five female patients undergoing post-operative radiotherapy for breast cancer. The accident involved a NEPTUN 10P linear accelerator. A transitory electrical power loss occurred, and following restart of the device, the patients received considerably higher doses than planned. Prescribed doses were 2–2.5 Gy per fraction from an 8 MeV electron beam. EPR assessment of rib samples resulted in dose estimates of 60–80 Gy. Medical examination revealed local injuries in the five patients, which worsened over time. Surgical intervention was necessary in all cases. The condition of four patients improved with the use of hyperbaric oxygen therapy [I22].

117. *United Kingdom, 2006.* In January 2006, a 15-year-old female patient was receiving radiotherapy for a brain tumour at an oncology centre in Glasgow. Twenty planned fractions of 1.75 Gy (35 Gy total) were to be delivered using a linac system, but owing to a dose planning error undiscovered until the 19th fraction, the estimated delivered dose was 55.5 Gy [J5].

D. Summary

118. Those at risk in the medical use of radiation include patients, physicians and staff, as well as those involved in changing sources, repairing devices, and so on. Human error has been a common cause of these accidents in the medical field. Examples of errors include delivering the radiation dose to the wrong patient or to the wrong location, giving the wrong dose because of errors in treatment planning and failure to use survey equipment/monitors as intended. The IAEA [I25] and ICRP [I24] have catalogued over 100 radiotherapy accidents, and table 6 lists 32 examples of serious radiation accidents in the medical field. It is noteworthy that such accidents were sometimes not recognized, because injuries were not always evident until some time after a procedure, or symptoms were masked by the severity of the underlying disease process. Both underexposure and overexposure to radiation have had serious consequences. Only overexposures have been included in this annex. The Committee considers it likely that some deaths and many injuries in the medical use of radiation have not been reported.

VI. OTHER ACCIDENTS

A. Transport accidents

119. Millions of packages of radioactive material are safely transported throughout the world each year. Most of these materials are for medical or general industrial use. Many packages are manually handled and are transported by road, or sometimes by air, sea or rail. Some packages require remote handling because of their weight. Road and rail traffic is often through urban areas, and members of the public may be in close proximity to the packages. In the event of an accident, there could be a local release with some atmospheric or aquatic dispersion [H1, I16].

120. Accidents do occur during transport, although any consequences are normally limited by built-in safety features of the packages/containers and by adherence to regulatory controls, including emergency response procedures. (See reference [I17] for detailed information regarding accident frequency, types and consequences.) A recent United Kingdom study of accidents and incidents over the period 1958–2004 concluded that the most serious radiological consequences occurred as a result of transporting improperly packaged industrial radiography sources [H10].

121. Less commonly, accidents have occurred during military and civilian movement of radiological or nuclear materials by aircraft, ship, submarine or spacecraft (see table 7). These accidents have involved small nuclear reactors, RTGs, nuclear weapons, nuclear waste and other radioactive shipments [B1, I16, I18, T1]. A number of these accidents have resulted in loss of life due to causes other than radiation. Again, consequences have been limited by the substantial built-in safety features, by adherence to the controls required for transport, and by the emergency response and recovery procedures utilized.

122. Table 7 summarizes 24 accidents involving sea, air and space vehicles. With the exception of the submarine accidents in the former Soviet Union (see table 1), these accidents did not lead to early acute effects of radiation exposure. Some of them, however, did lead to widespread dispersion of radioactive material in the environment. Military activities have involved at least two documented serious transport accidents that led to environmental contamination: the accidents at Palomares, Spain, and Thule, Greenland. These accidents were described in the UNSCEAR 1993 Report [U6]. More detailed information on accidents and losses in the marine environment can be found in reference [I18].

B. Suspected malicious act

123. While malicious acts are clearly not accidental, they are in principle of interest for the Committee's assessments if they lead to early acute health effects of radiation or to widespread significant population exposures. The Committee has not reviewed such events comprehensively in the context of this report. Nevertheless, it considered it appropriate to note a recent suspected malicious act that received much media attention.

124. On or about 1 November 2006, a Russian living in the United Kingdom was allegedly poisoned with ^{210}Po [H9]. He died on 23 November 2006 [H6]. The death caused widespread public interest. An extensive public monitoring programme revealed no public health consequences for open public spaces. More than 700 persons in the United Kingdom were tested for ^{210}Po contamination. Of these, more than 100 showed ^{210}Po concentrations in urine indicating some contamination from the incident, but fewer than 20 had results indicating committed effective doses of greater than 6 mSv [H7, U17].

VII. SUMMARY

125. Early acute (deterministic) health effects of radiation exposure have occurred as a result of accidents or malicious acts. Some serious accidents have additionally led to significant population exposures (at levels below that for deterministic effects) owing to widespread dispersion of radioactive material in the environment.

126. This annex categorizes and summarizes radiation accidents that have resulted in early acute health effects, deaths and/or major environmental contamination during the past 60 years (tables 2–6). Selected examples of each accident type have been briefly described in the text to provide insight into the nature of the reported accidents, their medical consequences and the associated radiation doses that resulted in injuries and deaths.

127. Table 8 presents an overall summary of the number of accidents reported in each category over time. Table 9 presents published estimates of the collective doses for a spectrum of accidents that have led to significant population exposures owing to environmental contamination. Table 10 presents a summary of the numbers of deaths and early health effects that have been reported owing to radiation accidents over the last 60 years. These summaries cannot be deemed complete. For example, it was not possible to use fully the summary information in table 1.

128. In more than 60 years (1945–2007) of work at nuclear facilities there have been 35 serious radiation accidents reported. Seven of these caused off-site releases of radioactive materials, with potential for significant population exposures. Of the 35 reported accidents, 24 were in facilities related to nuclear weapons research, development and production, and to the reprocessing of nuclear fuel for weapons programmes. Other accidents occurred in power reactor research, development and operation, and in the reprocessing of nuclear fuel. Excluding the 1986 accident at Chernobyl, 32 deaths are known to have occurred as a result of radiation exposure in accidents at nuclear facilities, and 61 workers suffered radiation injuries requiring medical care. The incidence of accidents in these facilities has fallen; most of the deaths and injuries occurred in the early years of research and development in the context of nuclear weapons programmes. Only one criticality accident, with the death of two workers, has occurred in the past 20 years.

129. Eighty accidents were reported at other industrial facilities utilizing radiation sources, accelerators and X-ray devices. Nine deaths were reported in these accidents, and 120 workers were injured, with the hands being a common site of injury. Serious injuries frequently led to amputations. Acute radiation syndrome developed in some injured workers, and multiple amputations were necessary in some cases.

130. Thirty-four accidents have been attributed to lost, stolen or abandoned sources (orphan sources) since 1960. These accidents are known to have resulted in the deaths of 42 members of the public, including children. In addition, ARS, serious local injuries, internal contamination or psychological problems necessitated medical care for hundreds of persons. The number of reported accidents involving orphan sources has increased in the past 20 years (see table 8). It is noteworthy that six accidents were associated with abandoned medical therapy units.

131. Reports of accidents in academic and research facilities have been rare, with 22 accidents since 1960 and only four within the past 20 years. Most of these accidents resulted in injuries to the hands.

132. The Committee considers that accidents associated with the medical use of radiation in diagnosis and treatment may have been under-reported. There have been relatively few reports of serious accidents, considering the extremely large number of procedures performed annually throughout the world (annex A). Since 1967, 32 accidents with 46 deaths have been considered here. However, there have been a large number (623) of persons who developed early acute (deterministic) health effects as a result of these accidents. Delays in recognizing errors led to greater numbers of persons being injured. The 32 accidents considered here involved serious overexposures to radiation, but underexposures can also have serious consequences for patients.

133. The extensive worldwide civilian transport of radioactive materials has not resulted in any human injuries related to radiation exposure. Accidents have occurred during military transport of radioactive materials. Some resulted in, or had the potential for causing, environmental contamination, and some have resulted in the loss of lives (although not necessarily because of the radioactivity). A limited number of spacecraft carrying radioactive material have burned up on re-entry into the earth's atmosphere or have crashed, resulting in significant releases of radioactive material to the environment. However, there is no documented evidence of anyone sustaining injury from these events.

134. This annex does not explicitly address observable late effects due to ionizing radiation exposure. However, for comparative purposes, table 9 presents estimates for collective doses sustained by local and regional populations from a spectrum of accidents that led to dispersion of radioactive material in the environment. One accident dominates the collective dose, namely the 1986 Chernobyl accident, on which the Committee has prepared a dedicated annex, annex D, “Health effects due to radiation from the Chernobyl accident”.

135. Serious radiation accidents have been rare occurrences. Much information has been published about these accidents, but information about some less serious accidents remains unreported in the literature. Human error, carelessness, failure to follow procedures and safety guidelines, defective equipment or defective repair, inadequate training, loss of control and source abandonment, and other conditions have led to accidents in the past 60 years, and will probably lead to accidents in the future.

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Table 1. Major types of radiation accident on the territory of the former USSR and the nature of their early effects
As recorded up to 30 June 2003 [I27]

Type	*Number of radiation accidents*	*Number of people with significant clinical symptoms*						
		Total (ARS + LRI)[a]	*ARS severity grade*[b]				*Died*
			I	*II*	*III*	*IV*	
Radioisotope units and their sources (total)	92	170	49	27	11	6	16
^{60}Co	17	28	15	9	6	3	3
^{137}Cs	19	59	13	7	1	—	9
^{192}Ir	37	54	10	3	—	—	1
Other gamma emitters	8	10	2	1	—	—	—
beta/gamma emitters	2	2	—	—	—	—	—
beta emitters	9	17	9	7	4	3	3
X-ray units and accelerators (total)	39	43	—	—	—	—	—
X-ray units	27	30	—	—	—	—	—
Electron accelerators	9	10	—	—	—	—	—
Proton accelerators	3	3	—	—	—	—	—
Reactors and critical fissile materials (total excluding Chernobyl accident)	33	82	73	39	25	13	13
Criticality	16	42	42	30	20	10	10
Reactors (other than criticality)	17	40	31	9	5	3	3
Mayak Production Association (1949–1956) with LRI	168[c]	168	—	—	—	—	—
Nuclear submarine	4	133	85	29	19	12	12
Others	12	17	7	3	2	2	2
Total excluding Chernobyl accident	348[c]	613	214	98	57	33	43
Chernobyl accident	1	134	134	93	43	21	28
Total	349[c]	747	348	191	100	54	71

[a] Acute radiation syndrome (ARS) and local radiation injuries (LRI).
[b] ARS severity grades: I – mild, II – moderate, III – severe, IV – extremely severe.
[c] Each LRI case at Mayak Production Association (1949–1956) is considered as a separate accident.

Table 2A. Accidents at nuclear facilities: Related to nuclear weapons programmes

Year	*Location*	*Operation/ installation*	*Main cause of accident*	*Early*		*Nature of exposure/health consequences*	*Ref.*
				Deaths	*Effects*		
			Criticality accidents				
1945	United States: Los Alamos, New Mexico	Nuclear research facility	Unsafe procedure; during a critical assembly experiment, a scientist's hand slipped, allowing a tungsten carbide brick to fall into the assembly	1	1	Experimenter received 5.1 Gy whole-body dose and died 28 days after exposure; a guard received 0.5 Gy	[L1]
1946	United States: Los Alamos, New Mexico	Nuclear research facility	Unsafe procedure; a critical assembly reflected by beryllium was being demonstrated; the reflector slipped, allowing a criticality excursion	1	6	Man performing demonstration died nine days after exposure of 21 Gy; seven others had doses of between 0.37 and 3.6 Gy	[L1]
1952	United States: Argonne, Illinois	Nuclear research facility	Failure to follow operating procedure during replacement of control rod		3	Radiation doses to four workers were 1.36, 1.27, 0.6 and 0.09 Gy	[L1]
1953	USSR: Chelyabinsk	Nuclear research and reprocessing facility	Poor design; unfavourable geometry used for mixing, dilution, storage, etc. of plutonium nitrate products		2	Chief operator received 10 Gy non-uniform whole-body exposure with maximum dose of 30 Gy to legs; survived moderate ARS, and both legs were amputated; another worker survived moderate ARS (1.5–2.0 Gy)	[G5, L1, V1]
1957	USSR: Chelyabinsk[a]	Nuclear research and reprocessing facility	Poor design; accumulation of uranyl oxalate in unsafe geometry	1	5	Operator exposed for approximately 10 minutes, dose estimate was more than 10 Gy, died 12 days after exposure; five others had ARS (2.0–6.0 Gy) but recovered	[G5, L1, V1]
1958	USSR: Chelyabinsk	Nuclear research and reprocessing facility	Unsafe geometry during draining of uranium solution; neutron reflector contributed to criticality	3	1	Three workers died in 5–6 days; doses estimated at 40–50 Gy; a fourth person was approximately 3 m away and survived, with continuing health problems and loss of eyesight	[B11, G5, K2, L1, V1]
1958	United States: Oak Ridge, Tennessee	Nuclear processing facility	Valve leakage led to an unplanned transfer of enriched uranium solution to a 55-gallon (208 L) drum. Unsafe geometry resulted in a criticality		8	Doses of the eight injured ranged from 0.7 to 3.65 Gy; all survived	[A1]
1958	United States: Los Alamos, New Mexico	Nuclear research facility	Unsafe geometry occurred when plutonium solids were washed from two vessels into one	1		Operator died 36 hours after the accident; dose to upper torso was estimated to be 120 Gy; two others had whole-body doses of 1.34 and 0.53 Gy but no ill effects	[L1]
1961	United States: Idaho Falls, Idaho	Reactor research facility	Evidence suggests control rod was manually pulled out too fast, causing power rise	3 (trauma)		Two men were killed instantly from a steam explosion; a third man died two hours later as a result of head injury	[L1]
1961	USSR: Seversk, Siberia	Chemical processing facility	Criticality controls were not in place during condensing and evaporation of uranium hexafluoride		1	Process operator received a dose of about 2 Gy, with mild radiation sickness symptoms	[L1, V1]
1962	United States: Hanford, Washington	Processing facility	Improper control of solutions led to unfavourable geometry		1	One person received 1.1 Gy	[L1]
1963	USSR: Arzamas, Sarov	Nuclear weapons research facility	Violation of operating procedures		2	Two operators received doses of 3.7 and 5.5 Gy; both developed radiation sickness but survived; four others working in adjacent areas received low doses (0.07–0.0002 Gy)	[L1]

1964	United States: Wood River Junction, Rhode Island	Chemical processing facility	Human factors; labelled bottle indicated high concentration of U; contents were transferred to vessel and unsafe geometry resulted	1	2	Radiation dose to the operator was estimated to be 100 Gy; he died 49 hours after the accident; two individuals who entered the room received doses of 1 and 0.6 Gy	[K1, L1]
1968	USSR: Chelyabinsk-70	Reactor	Violation of procedures; failure to reposition a reflector	2		One technician received 20–40 Gy from gamma and neutron exposures and died three days later; a second technician received 5–10 Gy and died 54 days after the excursion	[L1]
1968	USSR: Chelyabinsk-40	Plutonium extraction facility	Inadequate design leading to unfavourable geometry of plutonium solution	1	1	Shift supervisor died on day 34 after receiving whole-body dose of more than 7 Gy and 50 Gy to the legs; the operator survived moderate ARS and subsequently had both legs and one arm amputated	[V1, V4]
1978	USSR: Siberia	Plutonium processing facility	Unfavourable geometry of plutonium ingots during packaging; deficient box design		1	Operator received approximately 2.5 Gy whole-body dose and 70 Gy to the hands, he survived moderate ARS, but with amputation of both hands; seven others received doses of between 0.05 and 0.6 Gy	[B11, L1, V1]
1997	Russian Federation: Sarov	Nuclear weapons research facility	Criticality; experimenter violated safety requirements	1		45 Gy neutrons and 3.5 Gy gamma whole-body dose; death in 66.5 hours	[I5, L1]
Other accidents with only on-site consequences							
1951	USSR: Chelyabinsk-40	Nuclear research and reprocessing facility	Unknown	1	4	External gamma and beta exposure causing local and/or ARS injury	[S2]
1952	USSR: Chelyabinsk-40	Nuclear research and reprocessing facility	Unknown	2		Internal contamination with tritiated water	[S2]
1954	USSR: Arzamas, Sarov	Nuclear weapons facility	Unknown	1		^{210}Po internal exposure; ARS	[S2]
1976	United States: Hanford, Washington	Research processing facility	Chemical explosion in glovebox		1	Worker injured by glass, nitric acid and intake of ^{241}Am; 8.6 Gy dose to bone marrow; death 11 years later of cardiovascular disease	[H2]
1986	United States: Gore, Oklahoma[b]	Uranium processing facility	Accidental rupture of a 14 ton (1 270 kg) cylinder of UF_6	1 (trauma)	7	Internal contamination of workers as well as low-level internal contamination of seven members of the public	[N3]

Accidents with releases to the environment and potential public health consequences

Year	*Location*	*Operation/ installation*	*Main cause and nature of accident*	*Ref.*
1957	USSR: Mayak Complex, Kyshtym[a]	Radiochemical plant	Overheating and resulting explosion of a storage tank led to release of 740 PBq of radioactive products	[U6]
1957	United Kingdom: Windscale, Cumbria	Graphite reactor	Overheating and fire resulted in release of 740 TBq ^{131}I; other radionuclides also released	[C2, G4, U6, U9]
1986	United States: Gore, Oklahoma[b]	Uranium processing facility	Accidental rupture of a 14-ton (1 270 kg) UF_6 cylinder resulting in a trauma death as well as low-level contamination of seven members of the public and of the environment	[N3]
1993	Russian Federation: Tomsk, Siberia	Reprocessing facility	Largest occupational group exposed were 1 920 persons involved in clean-up; build-up of gases in vessel followed by explosive rupture and explosion of flammable cloud	[I19]

a This accident is listed twice in this table under two categories: Criticality accidents and Accidents with releases to the environment and potentially significant population exposures.
b This accident is listed twice in this table under two categories: Other accidents with only on-site consequences, and Accidents with releases to the environment and potentially significant population exposures.

Table 2B. Accidents at nuclear facilities: Not related to nuclear weapons programmes

Year	*Location*	*Operation/ installation*	*Main cause of accident*	*Early*		*Nature of exposure/health consequences*	*Ref.*
				Deaths	*Effects*		
Criticality accidents							
1958	Yugoslavia: Vinca	Zero power reactor	Equipment failure (controls) caused nuclear excursion	1	5	Five individuals recovered from severe cases of radiation sickness; radiation doses ranged from 2.07 to 4.36 Gy	[L1, M4]
1965	Belgium: Mol	Experimental reactor	Failure to follow safety procedures, resulting in criticality excursion		1	Technician received non-uniform exposure of 3–40 Gy, with highest exposure to left foot; medical therapy was successful but left foot required amputation	[J3, L1, P2]
1971	USSR: Moscow	Power reactor research facility	Violation of operating procedures; control rods not actuated when water was added to tank containing fuel rods		3	Three persons received whole-body doses of about 3 Gy; two of them also received doses of about 20 Gy to the legs	[L1, V4]
1971	USSR: Moscow	Power reactor research facility	Faulty construction of the fuel assembly in the reactor; fuel rods fell into highly supercritical geometry	2	2	Technician received approximately 60 Gy and died in five days; supervisor received 20 Gy and died within 15 days; two others received 7–8 Gy and survived with long-term health effects	[L1, S2]
1983	Argentina: Buenos Aires	Critical facility	Failure to follow procedures in removing water from tank containing fissile material	1		Acute whole-body dose (17 Gy neutron and 20 Gy gamma); death two days after the accident from ARS (neurological) with radiopneumonitis in right lung	[L1, N1]
1999	Japan: Tokai-mura[a]	Fuel conversion plant	Workers unknowingly added higher enriched uranium into a tank bypassing criticality controls	2	1	Two fatalities (uneven exposures of 10–20 Gy Eq and 6–10 Gy Eq) and one person with whole-body dose of 1.2 to 5.5 Gy Eq	[A2, I6]
Other accidents with only on-site consequences							
1977	Argentina: Atucha	Nuclear power plant	Worker not wearing lead gloves		1	Wound contaminated with 3 800 Bq; mean beta dose of 364 Gy in period 1977–1985 and annual gamma dose of 0.04 Gy in 1 cm^3 of soft tissue	[U3]
1985	Czechoslovakia: Petrvald		Carelessness and inadequate equipment for work with transuranics		1	Intake through wound of 600 Bq of ^{241}Am; surgical excision of wound and administration of DTPA	[U3]
1989	Hungary: Paks	Nuclear power plant	Careless handling of detectors from reactor vessel		1	Whole-body dose of 29 mGy; 1 Gy to fingers of left hand; slight increase in chromosomal aberrations	[U3]

Accidents with releases to the environment and potentially significant population exposures

Year	*Location*	*Operation/ installation*	*Early*		*Main cause and nature of accident*	*Ref.*
			Deaths	*Effects*		
1979	United States: Three Mile Island, Pennsylvania	Nuclear power plant			Low water levels in reactor led to severe damage to fuel elements; 550 GBq ^{131}I released to the atmosphere. Limited evacuation of local population	[U6, U9]

1986	USSR: Chernobyl	Nuclear power plant	28 radiation induced, 2 trauma	106	Breach of operating rules and violation of safety procedures, combined with a flawed design resulted in a steam explosion, fire and destruction of the reactor. Whole-body doses of 1–16 Gy and localized doses to skin among plant staff and emergency personnel; 30 deaths; 106 others with ARS; medical treatment, including bone marrow transplants (101 others initially examined for ARS). Significant release of radionuclides into the environment (including 1 760 PBq of ^{131}I and 86 PBq of ^{137}Cs). Major evacuation and relocation of populations in the area. See annex D, "Health effects due to radiation from the Chernobyl accident" for more details	[U7]
1999	Japan: Tokai-mura[a]	Fuel conversion plant	2	1	Overfilling of tank led to criticality, neutron and gamma irradiation of people in the vicinity of the facility, and a very small release of fission products into the air. Limited evacuation of local population	[A2, I6]

a This accident is listed twice in this table under two categories: Criticality accidents and Accidents with releases to the environment and potentially significant population exposures.

Table 3. Accidents at industrial facilities

Year	Location	Industrial source/ installation	Main cause of accident	Early		Nature of exposure/health consequences	Ref.
				Deaths	Effects		
Sealed radioactive sources							
1968	Argentina	^{137}Co source	Worker carried a 0.5 TBq source in pocket for 18 hours		1	Whole-body dose of 0.5 Gy; maximum dose to thigh of 17 000 Gy; both legs amputated	[B6, B16]
1968	India	^{192}Ir source	Worker picked up a source that had fallen off a camera and kept it in his pocket for two hours		1	Skin dose of 130 Gy; ulcer took one year to heal	[A3]
1968	Germany	^{192}Ir source	Worker carried source in jacket pocket		1	Whole-body dose of 1 Gy; maximum dose to pelvis and thigh of 40–60 Gy	[S4]
1969	United Kingdom: Scotland	^{192}Ir source	Radiographer travelled with unshielded source		1	Whole-body dose of 0.6 Gy; dose to chest of 20–200 Gy; skin graft to chest required	[H4]
1972	China: Sichuan	^{60}Co irradiation facility	Accidental entry into the irradiation room		Unknown	0.5–1.47 Gy whole-body exposure to workers	[P1]
1973	USSR, Moscow area	4.2 PBq ^{60}Co industrial source	Operator entered room while source was in “on” mode		1	Operator survived whole-body dose of about 4 Gy	[B11]
1974	United States: New Jersey	4.4 PBq ^{60}Co industrial source	Failure to use survey meter prior to entering irradiation room		1	Non-uniform exposure estimated to be 4.1 Gy	[B2]
1975	Italy: Brescia	^{60}Co industrial irradiation facility	Lack of safety systems on conveyer entry point	1		Non-uniform exposure with mean whole-body dose of 12 Gy; haematopoietic syndrome; death 12 days after exposure	[J3, U3]
1975	USSR: Kazan	^{60}Co irradiation facility	Deterioration of safety system and improper actions to regain control		2	Whole-body doses of 3 and 5 Gy; dose to hands of 30 Gy and more than 50 Gy	[N10, U3]
1975	Iraq	^{192}Ir radiography source	Unknown		1	Whole-body dose of 0.3 Gy plus localized exposure of hand	[U3]
1976	United States: Pittsburgh, Pennsylvania	^{192}Ir radiography source	Unknown		1	Dose of 10 Gy to hand	[U3]
1976	USSR: Moscow region	^{60}Co irradiation facility	Technical failure of the equipment and improper entry		1	Whole-body dose of 4 Gy; moderate ARS	[U3]
1977	Czechoslovakia: Pardubice	^{192}Ir industrial irradiation source	Technical failure of the equipment and improper actions to bring source back under control		1	Whole-body dose of about 5 mGy; data insufficient for estimating local doses; bullous dermatitis of the thumb of the right hand; plastic surgery two years later	[U3]
1977	United States: Rockaway, New Jersey	^{60}Co industrial irradiation source of 18.5 PBq	Construction in the facility, lack of safety precautions and interlock failure		1	Whole-body dose of 2 Gy	[B2]

1977	United Kingdom	^{192}Ir radiography source	Operator working in a confined area held source for 90 seconds while conducting radiography on a weld		1	Equivalent whole-body dose of <0.1 Gy estimated on the basis of cytogenetic dosimetry; radiation burns on three fingers	[U3]
1977	Hungary: Györ	Industrial defectoscope	Failure of equipment to withdraw source into its container		1	Whole-body dose of 1.2 Gy; slight nausea, changes in blood and increased frequency of chromosomal aberrations	[U3]
1977	United Kingdom	Filling gaseous tritium light source	Broken inlet manifold led to the release and escape of 11–15 TBq of tritium		2	Whole-body doses of 0.62 and 0.64 Gy	[U3]
1977	South Africa: Sasolburg, Transvaal	^{192}Ir source	Faulty operation of pneumatically operated container and monitor; carelessness of operator		1	Whole-body dose of 1.16 Gy; amputation of two fingers, rib removal and skin grafts	[U3]
1977	Peru: Ona del Oleoducto	^{192}Ir source	Untrained personnel and lack of supervision; equipment neither registered nor authorized		3	Maximum doses of 164 Gy to hands; 0.9 Gy to lens of the eye; 2 Gy to the whole body; amputation of fingers of two people and effects on the left hand of another person	[U3]
1978	Argentina: Buenos Aires	^{192}Ir industrial source	Manual handling of source		1	Dose of 12–16 Gy, causing radiation burns on two fingers of left hand	[U3]
1978	United States: Monroe, Louisiana	^{192}Ir radiography source	Radiography of pipe welds on barge (off-shore drilling)		1	Localized exposure of hand; amputation of finger	[S1]
1979	Czechoslovakia: Sokolov	^{192}Ir industrial radiography	Technical failure of the equipment and inadequate monitoring during and after work		1	Whole-body dose of about 5 mGy; data insufficient for estimating local doses; bullous dermatitis of the third finger of the left hand and adjacent areas; plastic surgery two years later	[U3]
1979	France: Montpelier	^{192}Ir radiography source	Unknown		1	Whole-body and localized exposure; amputation of left arm	[U3]
1980	USSR: Leningrad	^{60}Co irradiation facility	Failure of safety device and improper entry	1		Whole-body dose of more than 12 Gy	[S2]
1980	China: Shanghai	^{60}Co irradiation facility	Entry into the irradiation chamber during power failure and with defective interlocks		1	Whole-body dose of 5.22 Gy and localized exposure	[U3, Y1]
1980	USSR	^{60}Co irradiation facility	Unknown		1	Dose of 50 Gy to lens of eye	[U3]
1981	Argentina: Buenos Aires	^{192}Ir industrial source	Source became detached and lodged in the delivery tube		2	Doses were not specified; radiation burns on fingertips	[U3]
1982	Norway: Kjeller	^{60}Co irradiation facility	Failure of safety device and failure to follow procedures	1		Mean whole-body dose estimated to be slightly higher than 20 Gy; death 13 days after exposure	[R1, S3]
1983	United Kingdom	Gamma radiography source	Inadvertent exposure to radiographer		1	Whole-body dose of 0.56 Gy	[U3]
1983	German Democratic Republic: Schwarze Pumpe	^{192}Ir industrial source	Technical defect and inappropriate handling		1	Dose to the right hand of about 5 Gy; acute and chronic radio-dermatitis (1st degree)	[U3]

Year	Location	Industrial source/ installation	Main cause of accident	Early		Nature of exposure/health consequences	Ref.
				Deaths	Effects		
1983	India: Muland, Bombay	^{192}Ir radiography projector	Operation by untrained personnel		1	Dose to the skin of 20 Gy and whole-body dose of 0.6 Gy; severe damage to fingers; four were amputated	[U3]
1984	Hungary: Tiszafured	^{192}Ir industrial defectoscope	Failure of equipment and careless handling of source		1	Whole-body dose of 46 mGy; 20–30 Gy estimated to fingers of left hand; irreversible necrosis at tip of one finger, surgically removed; slight increase in chromosomal aberrations	[U3]
1984	Argentina: Mendoza	^{192}Ir radiography source	Operator pushed source into camera using a finger		1	Dose of 18 Gy to finger (radiation burn on finger) and whole-body dose of 0.11 Gy	[U3]
1985	India: Yamunanager	^{192}Ir radiography projector	Violation of safe working practices associated with power failure in the workplace		2	Doses of 8–20 Gy to hands of both operators; damage to fingers; two fingers amputated from each individual	[U3]
1985	India: Visakhapatnam	^{60}Co radiography projector	Violation of safe working practices and lack of maintenance		2	Skin dose of 10–20 Gy to operator and 0.18 Gy to an assistant; damage to fingers; one finger amputated	[U3]
1986	China: Harran	^{60}Co irradiation facility	Power loss occurred and source was manually raised; workers entered room with source unshielded		2	Doses to workers of 3.5 and 2.6 Gy	[U3]
1986	China: Beijing	^{60}Co irradiation facility	Workers entered irradiation room when source was unshielded; failed drive system; door open		2	Doses to workers of 0.7 and 0.8 Gy	[U3]
1986	China: Kaifun City	^{60}Co source	Accidental exposure for about 1.5–2 minutes		2	Whole-body doses of 2.6–3.5 Gy; haemopoietic type of ARS	[W2, Y1]
1987	China: Zhengzhou City	^{60}Co irradiation facility	Accidental entry into irradiation room, 10–15 seconds		1	Estimated whole-body dose of 1.35–1.45 Gy; anorexia and nausea four hours later; severe damage to haemopoietic system with relatively slow restoration of white blood cells	[Y1]
1988	China: Liaoning	Radiography source	Workers handled source with hands		6	Local exposure of 0.1–12.6 Gy	[Z2]
1988	Czechoslovakia: Prague	Manufacturing of foils containing ^{241}Am for use in fire alarms	New rolling methods untested; poor radiation protection practice		1	Inhalation of 50 kBq of dispersed ^{241}Am; hospitalization and administration of DTPA; no clinical manifestations	[U3]
1988	China: Zhao Xian	^{60}Co irradiation facility	Accidental entry into irradiation room, about 40 seconds		1	Estimated whole-body dose of 5.2 Gy; ARS (bone marrow syndrome); after three years of follow-up, condition good	[U3]
1989	India: Hazira Gujarat	^{192}Ir radiography projector	Failure of safety management and improper maintenance		1	Dose of 10 Gy to fingers and whole-body dose of 0.65 Gy; radiation burns on fingers of both hands; fingers amputated	[U3]
1989	South Africa: Witbank, Transvaal	^{192}Ir industrial radiography source	Detached source; negligence of radiographer (source improperly attached) and failure of portable monitor to register detached source		3	Whole-body doses to three workers were 0.78, 0.1 and 0.09 Gy; computed effective dose to the most exposed worker was 2.25 Gy; this worker had amputation of right leg at the hip six months after exposure and amputation of three fingers one year after exposure	[U3]
1989	China	^{192}Ir radiography source	Unknown		1	Localized dose of 18.37 Gy	[U3]
1989	Bangladesh	^{192}Ir source	Unknown		1	Whole-body dose of 2.3 Gy	[U3]

1989	China: Beijing	^{60}Co source	Accidental exposure to source for about four minutes		2	Whole-body doses of 0.87 and 0.61 Gy; two workers suffered mild haemopoietic radiation sickness; recovered	[U3]
1989	El Salvador: San Salvador	^{60}Co irradiation facility	Deterioration of safety system and lack of understanding of radiation hazards	1	2	Three workers developed ARS after whole-body doses of 3–8 Gy; all three had local radiation injuries; one patient had both legs amputated; the most seriously irradiated patient had one leg amputated and died 197 days after exposure	[I1]
1990	South Africa: Sasolburg, Transvaal	^{60}Co industrial radiography source	Source left behind after radiography work; loss undetected because of inadequate monitoring; source handled by six people		6	One individual had right hand amputated above the wrist; three others had local radiation injuries; whole-body doses were less than 0.55 Gy	[U3]
1990	Israel: Soreq	^{60}Co irradiation facility	Improper entry and maintenance	1		10–20 Gy whole-body dose; death 36 days after exposure; bone marrow transplant and growth factors administered	[I2]
1990	China: Shanghai	^{60}Co irradiation facility	Entry into the irradiation chamber during power failure and with defective interlocks	2	5	Workers received doses of 2–12 Gy; the two who received 11 and 12 Gy died	[L2, P1]
1991	Belarus: Nesvizh	^{60}Co irradiation facility	Improper entry with source exposed	1		11–18 Gy whole-body dose; death in 113 days; haematopoietic growth factor administered	[I3]
1991	United Kingdom	Industrial radiography	Chronic incidents over 14 years	1	1	30 Gy to fingers, parts of two fingers amputated; estimated whole-body dose (chronic) of $<$10 Gy; death from acute myeloid leukaemia	[U3]
1992	China	Irradiation facility	Power loss and safety interlocks out of order		4	One worker with ARS	[P1]
1992	Switzerland	^{192}Ir radiography source	Jammed 700 GBq source; released by hand		1	Erythema of fingers: 3.5–10 Gy	[U3]
1993	United Kingdom	Gamma radiography unit	Improper procedures		1	Overexposure caused erythema and subsequent necrotic ulceration; hand dose of 30 Gy	[U3]
1998	China: Harbin	Unknown	Safety equipment failure		1	One worker with ARS	[P1]
2000	Brazil: Rio de Janeiro	^{60}Co industrial gamma radiography	Exposure during a routine service		1	Serious injuries to left hand	[D1]
2006	Belgium: Fleurus	^{60}Co irradiation facility	Malfunction of a command/control hydraulic system and failure of safety system		1	Worker entered an irradiation area and stayed approximately 20 seconds; he developed nausea and vomiting but did not seek medical attention until he developed massive hair loss; estimated whole-body dose of 4.4–4.8 Gy	[S9]
			Accelerators and X-ray devices				
1960	United States: Lockport, New York	Klystron tube X-irradiation	Shielding not in place during maintenance/repair		7	Non-uniform exposures; two individuals seriously injured, five others with less severe injuries	[H5]
1965	United States: Rockford, Illinois	Accelerator (10 MeV electrons)	Unknown		1	Man received 290 Gy to right ankle, 420 Gy to right hand and 0.05 Gy whole-body dose; amputations necessary	[G2, L3]
1967	United States: Pittsburgh, Pennsylvania	Linear accelerator	Failure of safety interlock system		3	One individual with severe radiation syndrome and multiple amputations; two other individuals had exposures of 3 and 1 Gy	[G2, G3]

Year	*Location*	*Industrial source/ installation*	*Main cause of accident*	*Early*		*Nature of exposure/health consequences*	*Ref.*
				Deaths	*Effects*		
1975	Germany	X-ray fluorescence unit	Carelessness and technical faults during repair		1	Estimated dose of 30 Gy to the fingers; reddening of two fingers ten days after exposure	[U3]
1975	Germany	X-ray equipment	Carelessness and technical defects		1	Welding seam test; estimated dose of 2 Gy to the stomach region	[U3]
1976	Germany	X-ray equipment	Inexpert handling of equipment		1	Estimated whole-body dose of 1 Gy; reddening of skin after 24 hours and radiation after-effects	[U3]
1977	Argentina: La Plata	X-ray crystallography	Shutter removed from crystallography set		3	Dose of 10 Gy to hands of one operator (radiation burns); doses to two workers not specified	[U3]
1978	France: Nancy	X-ray equipment	Unknown		1	Localized exposure of hand; amputation of finger	[U3]
1979	German Democratic Republic: Freiberg	X-ray fluorescence unit	Violation of safe working practice		1	Dose of 10–30 Gy to right hand and whole-body dose of 0.2–0.5 Gy; acute and chronic radiodermatitis (2nd and 3rd degree)	[U3]
1980	German Democratic Republic: Bohlen	Analytical X-ray unit	Violation of safe working practice		1	Dose of 15–30 Gy to left hand; acute and chronic radiodermatitis (2nd and 3rd degree)	[U3]
1980	Germany	Radiography	Defective equipment		2	Estimated dose of 23 Gy to the hand and an effective dose of 0.2 Gy	[U3]
1981	Germany	X-ray fluorescence device	Violation of safe working practice		1	Partial-body exposure with 20–30 Gy dose to the right thumb; extensive tissue damage developing over several months	[U3]
1983	Germany	X-ray equipment	Defective equipment		1	Partial-body exposure of approximately 6–12 Gy to regions of the body; localized physical changes	[U3]
1985	China: Shanghai	Accelerator	Entry into irradiation area while main motor was running		1	Worker incurred local radiation injury with dose of 25–210 Gy	[Z1]
1991	France: Forbach	Irradiation accelerator	Exposure to dark current		3	Severe skin lesions to one worker; less serious injury to two others	[C1, U3, Z3]
1991	United States: Baltimore, Maryland	Accelerator	Exposure to dark current during maintenance		1	55 Gy to fingers; most required amputation	[D3]
1992	Italy	X-ray spectrometer	Improper procedure during maintenance		1	Acute radiodermatitis of fingers of both hands	[S6]
1993	United Kingdom	~160 kV radiography unit	Improper procedures		1	Erythema of hands leading to necrotic ulceration	[I26]
1994	Mexico: Lazarus Cardenas	X-ray spectrometer	Failure to de-energize device prior to repair		1	Amputation of portion of finger necessitated	[B8]
1995	Brazil	X-ray diffraction unit	Poor maintenance of device allowing open back window		3	Acute radiodermatitis of hands caused by low-energy X-rays	[V3]
1999	United States	Electron beam device	Residual beam exposed operator's hand during manufacture testing		1	Skin dose to hand estimated to be 50 Gy	[M1]

Table 4. Accidents involving orphan sources

Year	Location	Operation/ installation	Main cause of accident	Early		Nature of exposure/health consequences	Ref.
				Deaths	Effects		
1960	USSR: Moscow	^{137}Cs source	Person deliberately placed source in belt of trousers and around body for suicide	1		Whole-body dose of 14.8 Gy; maximum dose to several points of skin of 1 650 Gy; death on day 18	[D2]
1962	Mexico: Mexico City	^{60}Co source (0.2 TBq)	Unsecured source removed from site	4	1	Family died as a result of exposure. The 10-year-old boy had a protracted (four months) exposure of 47 Gy; the 3-year-old child received a dose of 28.7 Gy, the 27-year-old pregnant mother 35 Gy and the 57-year-old grand-mother 30 Gy; the father's exposure over approximately seven months was 120 Gy and he survived	[M6]
1963	China: Hefei City, Sanli'an	^{60}Co source (0.43 TBq)	Abandoned source taken to farmer's home	2	4	Farmer's dose was 80 Gy; source was in his pocket for approximately 52 hours; his 7-year-old brother had the source in his pocket for 18 hours, receiving a dose of 40 Gy; both failed to respond to medical treatment; the other four people exposed had doses of 8, 6, 4 and 2 Gy and survived	[P1, W2]
1971	Japan: Chiba	^{192}Ir source	Lost source picked up by worker		6	Three patients had minimal blood changes and were hospitalized for two months; three others had ARS and local radiation injuries	[H3]
1973	Mexico: Tula, Hidalgo	^{137}Cs source	Source fell out of its container in truck and was picked up and put in pocket		1	One person suffered injury to hand, thigh and buttock, leading to amputa-tion of left leg and one finger; estimated local dose to thigh of 1 386 Gy	[N5]
1975	USSR: Sverdlovsk	^{60}Co medical source (17 TBq)	Source fell unnoticed during transport for burial	1	2	Driver died from very severe ARS (7 Gy) on day 33; two others (about 3 Gy) survived moderate ARS	[B11, S2]
1977	South Africa	^{192}Ir source	Source picked up from factory floor and taken home		1	Burns of hands and chest; skin graft on chest required; whole-body dose of 1.1 Gy; maximum skin dose of 50–100 Gy; three individuals with low-level symptoms	[L5]
1978	China: Herran	^{137}Cs source	Unused source was taken to worker's home		29	Doses of 0.01–0.53 Gy to bone marrow of individuals	[U3]
1978	Algeria	^{192}Ir radiography source	Source fell out of truck and was picked up	1	6	One fatality (member of public); source found by boys aged 3 and 7 years; one foetus also aborted	[J2]
1979	United States: Los Angeles, California	Lost ^{192}Ir radiogra-phy source	Failure of radiographer to check source storage		5	Individual who carried source in hip pocket developed severe lesion to the right buttock from a dose at the skin surface of 800–4 000 Gy; whole-body dose was 0.75–1 Gy; four individuals had minor skin injuries; 11 persons were involved	[R2]
1980	USSR: Yuzhno-Sakhalinsk	^{192}Ir radiography source	Taken from improper storage by 2 children for play; one put it in jacket pocket	1	1	First boy received more than 15 Gy to the hands, and two spots on abdo-men received more than 20 Gy; he died after 3 months from poor liver function; second boy received 8 Gy to the hand, and developed not severe local radiation injury	[N11]
1982	China: Hanzhong	^{60}Co source	Source was stolen	Not specified		Doses ranged from 0.42 to 3 Gy	[W1]

Year	Location	Operation/ installation	Main cause of accident	Early		Nature of exposure/health consequences	Ref.
				Deaths	Effects		
1982	USSR: Azerbaijan	^{137}Cs military source	Two abandoned sources circulated among soldiers	5	17	Five of the most exposed had very severe radiation injury to one or both thighs and lower abdomen (doses from 500 to 900 Gy); one died on day 26, three others in spite of treatment within 3-4 months; the fifth died after a year. Seventeen people developed local radiation injuries	[N11]
1982	USSR: Turkmenistan	^{60}Co medical source	Abandoned device containing the source was dismantled by hospital patients; a man found the source and took it home; on the next day, 11 other people touched it		13	A patient who dismantled the device and the man discovering the source received whole-body doses of 2 Gy and 6 Gy, and doses to the hands of 30 Gy and 700 Gy respectively. Both hands of the latter person were amputated. Eleven other people developed local radiation injuries to the hands	[N11]
1982	USSR: Ukraine	^{137}Cs source		2	2	ARS and local injuries	[S2]
1983	Mexico: Ciudad Juarez	^{60}Co teletherapy source	Device disassembled and sold to a scrapyard; lack of control		10	Source contained ^{60}Co in tiny pellets of 2.77 GBq each; total activity was 16.6 TBq	[B3]
1984	Morocco	^{192}Ir radiography source (603 GBq)	Source was taken home, kept in family bedroom and discovered after 80 days	8	3	Protracted exposures resulted in deaths of four adults and four children (ages 4, 5, 7 and 8)	[M2, M5]
1985	China: Mudanjiang	^{137}Cs source	370 GBq source was found and taken home	1	2	Accumulated local doses were 8–10 Gy; one person died after 22 months	[Y1]
1987	Brazil: Goiânia	^{137}Cs radiotherapy device	Abandoned device containing caesium source, disassembled	4	129	21 persons had doses in excess of 1.0 Gy (up to 7 Gy); 50 persons were admitted to hospital or primary care units; 79 persons received dispensary care. ARS, skin injuries and internal contamination were problems. Local environmental contamination occurred	[I11, I12]
1988–1991	USSR: Ukraine	^{137}Cs source (2.6 TBq)	Source found embedded in bedroom wall	2	1	Chronic exposure. Young boy had radiation injury of foot skin with transformation into sarcoma, and died; his 9-year-old brother had radiation injury of the foot and bone marrow depression with transformation into leukaemia, and died; a third person incurred mild chronic skin radiation injury and survived	[M2, S2]
1992	China: Xinzhou	Former ^{60}Co irradiation facility	Farmer working on the site demolishing the facility picked up source; it went with him to the hospital	3	11	14 persons were exposed to doses of >0.25 Gy; three received doses of >8 Gy and died	[P1]
1993–1998	Turkey: Istanbul	Two ^{60}Co medical therapy sources	Poor source security		18	Five persons with ARS (up to 3 Gy), one with lesions on one hand	[I7]
1994	Estonia: Tammiku	1.6 TBq ^{137}Cs source from part of an irradiator	Theft of source and poor source security	1	5	Whole-body exposure of up to 4 Gy, variety of localized exposures of up to 1 800 Gy	[I13]
1995	Russian Federation	^{137}Cs source (48 GBq)	Unshielded source in truck for approximately five months	1		Source located in door pocket of truck; protracted dose of 7.9 Gy (whole-body); local dose of approximately 65 Gy; death at 22 months after discovery	[B7, S7]
1995	France	^{192}Ir gamma radiography source	Direct handling of 1 TBq source		1	Erythema of hands; estimated local dose of >30 Gy	[U3]

1995	France	^{137}Cs density gauge source	Unknown		1	Erythema of hands	[U3]
1996	Islamic Republic of Iran: Gilan	^{192}Ir radiography source	Poor procedures; failure of lock on radiography container		1	Labourer found source and put it in breast pocket; 2–4 Gy whole-body dose, 40 Gy to chest	[I21]
1996–1997	Georgia: Lilo	^{137}Cs training sources, ^{60}Co source and sighting devices	Abandoned sources at a military training centre		11	12 sources (^{137}Cs) were found; later 200 discarded sighting devices (^{226}Ra) were found; local injuries and some individuals with systemic effects	[I20]
1999	China: Henan	^{60}Co "ex-service" therapy source	Source found in residence of farmer		7	Seven persons received high doses (1.0–6.0 Gy)	[X1]
1999	Peru: Yanango	1.37 TBq ^{192}Ir source	Welder found industrial radiation source		2	Source found and placed in trouser pocket; severe exposure to right thigh, perineum and hip led to amputation, colostomy; welder's wife received local injury while sitting on trousers containing source	[I8]
2000	Thailand: Samut Prakarn	^{60}Co radiotherapy sources	Poor source security leading to three old therapy units ending up in scrapyard	3	7	Ten persons were hospitalized; three died	[I9]
2000	Egypt: Meet Halfa	^{192}Ir radiography source	Source lost by worker testing pipe welds was found by farmer	2	5	Abandoned source was taken home by farmer; he died 40 days later; his son died after 30 days of exposure. Dose estimates were: father 7.5–8 Gy; son 5–6 Gy; and five others 3.5–4 Gy	[E1, I10]
2000	Russian Federation: Samara Oblast	^{192}Ir radiography source	Insufficient safety training of radiographers		3	Three radiographers received whole-body doses of 1–3 Gy; one of them had hand burns due to localized doses of 30–70 Gy	[S8]
2001	Georgia: Lia	^{90}Sr radioisotope thermoelectric generator	Two abandoned sources		3	Woodsmen found thermally hot objects and used them as heaters. They suffered systemic effects; two developed severe local injuries	[I23, J1]

Table 5. Accidents at academic and research facilities

Year	*Location*	*Operation/ installation*	*Main cause of accident*	*Early*		*Nature of exposure/health consequences*	*Ref.*
				Deaths	*Effects*		
Sealed radioactive sources							
1960	United States	^{60}Co source	Source detached during irradiation of samples		1	Graduate student exposed to 7 TBq ^{60}Co whole-body dose of 2.5–3 Gy; maximum skin dose of 30 Gy	[R3]
1962	USSR: Moscow	^{60}Co source (1.9 PBq)	Violation of safe working practices, improper entry to irradiation room		1	Whole-body dose of 2.5-3.0 Gy and 12 Gy to the hand	[G5]
1971	United States: Tennessee	^{60}Co irradiation	Equipment malfunction and operational error		1	Technician was in front of unshielded source for approximately 40 seconds; whole-body dose of <2 Gy, dose to hand of 12 Gy	[V2]
1978	Sweden: Nykoping	Research reactor	Instructions for work not followed		1	Dose of 30 Gy to skin of hand; radiation burn to skin	[U3]
1979	Germany: Rossendorf	Research reactor	Neutron activation of a sample grossly underestimated		1	Dose of 20–30 Gy to right hand; acute and chronic radiodermatitis (2nd and 3rd degree) and oedema	[U3]
1980	Germany: Rossendorf	Radiochemical laboratory	Defect in protective glove led to contamination with ^{32}P		1	Dose of 100 Gy to skin of left hand; no clinical symptoms	[U3]
1983	German Democratic Republic: Leipzig	Radiochemical laboratory	Explosion of vial containing ^{241}Am solution		1	Committed effective dose of 0.076 Gy	[U3]
Accelerators and X-ray devices							
1972	United Kingdom	X-ray crystallography	Shutter was removed prior to and during servicing		1	Dose to two fingers of 15–20 Gy, resulting in burns	[L4]
1974	United States: Davis, California	X-ray diffraction unit	Safety interlock bypassed; failure to note warning light		2	Localized exposure of hands; one person had serious injuries	[B4]
1975	Germany	X-ray fluorescence unit	Violation of safe working practice		1	Dose of 1.2–2 Gy to finger; acute radiodermatitis	[U3]
1977	USSR: Kiev	Proton accelerator (40 MeV)	Violation in beam testing examinations		1	Localized doses to hands of 12–30 Gy	[A5, B12]
1977	United States: Berkeley, California	X-ray	Safety interlock failure		1	Loss of two fingers on one hand and one finger on the other hand	[T2, U3]
1978	USSR: Protvino	Proton accelerator (70 GeV)	Improper entry to adjust sample in beam		1	Beam pierced man's head; middle ear destroyed, facial nerve injured, abortive epilepsy developed	[B13]
1978	United States	Accelerator	Unknown		1	Localized exposure to abdomen, hands, thighs	[U3]

1978	USSR: Leningrad	Electron accelerator (12.7 MeV)	Improper entry		1	Localized doses to back and chest of more than 20 Gy and 8 Gy respectively. Local radiation injury of skin and spinal cord	[A5]
1981	Germany: Berlin	Analytical X-ray unit	Violation of safe working practice		1	Dose of 5 Gy to the left hand; acute radiodermatitis (1st degree)	[U3]
1982	Germany: Berlin	Analytical X-ray unit	Violation of safe working practice		1	Dose of 6–18 Gy to the right forefinger; acute radiodermatitis (2nd degree)	[U3]
1984	Peru: Lima	X-ray diffraction equipment	Fault of supervision, deliberate exposure from lack of knowledge of risk; equipment not registered with authorities		6	Localized doses of 5–40 Gy to fingers; skin burns and blistering leaving residual scar tissue	[U3]
1988	German Democratic Republic: Trustetal	Analytical X-ray unit	Technical defect		2	Maximum dose of 4 Gy to the hand of one person; acute radiodermatitis (1st degree) in one person	[U3]
1988	German Democratic Republic: Jena	Analytical X-ray unit	Violation of safe working practice		1	Dose of 3 Gy to left hand; acute radiodermatitis (1st degree)	[U3]
1992	Vietnam: Hanoi	Research accelerator	Improper entry to adjust sample in beam		1	Individual unknowingly exposed hands; dose to left hand of 10–25 Gy, to right hand 20–50 Gy; fingers and one hand amputated; whole-body dose estimated to be 1–2 Gy	[I4]
1994	United States: Davis, California	X-ray diffraction equipment	Bypass of safety interlock to effect repair		1	Exposure of both hands with formation of bullae	[B4]

Table 6. Accidents associated with the medical use of radiation

Year	*Location*	*Operation/ installation*	*Main cause of accident*	*Early*		*Nature of exposure/health consequences*	*Ref.*
				Deaths	*Effects*		
1966	USSR: Kaluga	X-ray equipment (50 kV)	Poor maintenance	1		Localized dose to face and head of more than 20 Gy. Local radiation injury developed into atrophy and scars of face, loss of left eye; bone necrosis; death in year 7 of late radiation encephalitis	[B14, G5]
1967	India	^{60}Co teletherapy	Source gain during transfer		1	Skin dose to hand of 80 Gy	[B5]
1968	United States: Wisconsin	Nuclear medicine, ^{198}Au	Higher than prescribed dose administered	1		Acute whole-body radiation exposure from internal source; patient died 69 days after the misadministration	[B9, M3]
1972	China: Wukan	^{60}Co radiotherapy	Source fell from holder and was unnoticed for 16 days; design of device did not meet international standards		28	20 patients and eight workers received doses in the range 0.5–2.45 Gy	[W1]
1974–1976	United States: Riverside, Ohio	^{60}Co teletherapy	Use of incorrect decay curve, lack of periodic calibration of output		426	Overexposure of 426 patients; dose rates had been underestimated by 10–45%	[M1]
1975	Germany	X-ray equipment	Probable violation of safe working practice in maintenance		1	Dose in excess of 1 Gy to head and upper torso	[U3]
1975	Argentina: Tucumán	^{60}Co teletherapy	Failure of source mechanical mechanism		2	Technician and physician both received high doses to fingers; radiation burns on fingers	[U3]
1977	Germany	^{192}Ir radiography	Defective equipment		1	Estimated dose to hand of about 5 Gy and effective dose of 0.01 mGy; temporary reddening of fingers	[U3]
1977	United Kingdom	Laboratory	Accidental contamination of laboratory workers		2	Thyroid dose of 1.7 Gy to one person from a ^{125}I intake of about 1 MBq; a low dose to another person	[U3]
1979	Argentina: Paraná	Diagnostic radiology	Faulty wiring led to emission of X-rays when the top of the fluoroscope was open		1	Nurse received a whole-body dose of 0.94 Gy; slight bone marrow depression	[U3]
1981	France: Saintes	^{60}Co radiotherapy source	Direct hand contact with 137 TBq ^{60}Co source during source loading		3	Two victims had both hands amputated owing to severe injury caused by exposures estimated at >25 Gy; a third victim had a large portion of his right hand amputated	[N7]
1982	Argentina: La Plata	X-ray therapy facility	Operator looked through window while changing tubes without recognizing system was energized		1	Whole-body dose of 0.12 Gy and dose of 5.8 Gy to lens of eye; cataracts in both eyes	[N2]
1985	United States: Marietta, Georgia	Therac-25 accelerator	Problem of integration of hardware and software of system		1	Loss of function of one arm and shoulder	[N2]
1985	Canada: Hamilton, Ontario	Therac-25 accelerator	Problem of integration of hardware and software of system		1	Severe burn on hip; patient died of cancer four months after the accident	[N2]
1985	United Kingdom	Laboratory	Technician cut finger; poor technique		1	Technician cut his finger while wearing a glove contaminated with ^{125}I; sucked cut finger, which resulted in an intake of about 740 MBq and a thyroid dose of 400 Gy	[U3]

1986	United Kingdom	^{60}Co radiotherapy	Exposure during source changing		1	Dose of 15 Gy to hand; erythema, blistering at two weeks	[U3]
1986	United States: Tyler, Texas	Therac-25 accelerator	Problem of integration of hardware and software of system	1		Loss of function of arm and both lower extremities; skin injuries; periodic nausea and vomiting; radiation-induced myelitis at C5, C6 level of cervical cord; death five months after the accident	[N2]
1986	United States: Tyler, Texas	Therac-25 accelerator	Problem of integration of hardware and software of system	1		Victim died three weeks after the accident; acute high dose radiation injury to the right temporal lobe of the brain and brain stem	[N2]
1987	United States: Yakima, Washington	Therac-25 accelerator	Problem of integration of hardware and software of system; operator error		1	90–100 Gy accidentally delivered to chest of patient; the patient subsequently died of oesophageal carcinoma	[N2]
1987–1988	United States: Maryland	^{60}Co therapy	Treatment planning; computer file was not updated after source change		33	33 patients received whole-brain doses 75% greater than prescribed; 20 patients died either during or after completion of therapy	[I24]
1988	Netherlands: Rotterdam	Sagittaire accelerator	Leakage of radiation during therapy		1	Severe skin reactions of thorax, head and upper arm; dose estimated at 10–20 Gy	[W3]
1990	Spain: Zaragoza	Linear accelerator	Assumption that meter on control panel was stuck, although electron energy had been modified by technician	15	12	27 patients received doses 3–7 times higher than intended; 15 died with radiation exposure as primary cause; others had major disabilities	[I24, S5]
1992	United States: Indiana, Pennsylvania	Brachytherapy source	Source dislodged; failure to check for source's return to shielded holder	1		Source remained in patient for four days; 94 other individuals were exposed at the clinic, nursing home and other areas	[I24, N4]
1994	United States	High-dose-rate brachytherapy	Treatment planning errors		1	Patient was given a dose of 12 Gy to the vaginal area instead of the prescribed dose	[N6]
1996	Costa Rica: San José	^{60}Co teletherapy	Error in calculating dose rate	17	46	Exposures were significantly higher (50–60%) than prescribed	[I14, I24]
1996	Russian Federation, Moscow	Accelerator accident	Accidental dose rate increase		1	Localized dose of more than 100 Gy. Acute, high dose radiation injury to left part of chest	[B11]
2000–2001	Panama: Panama City	^{60}Co teletherapy	Misuse of treatment planning system	5	23	Patient doses were doubled; five died of radiation injuries; two deaths were questionable; nine of 16 survivors had marked or catastrophic complications	[B10, I15]
2001	Russian Federation: Nizhny Novgorod	X-ray cosmetic therapy	Systematic errors in dose rate calculations		9	Local radiation injuries to facial skin – dry and moist desquamation	[B11]
2001	Poland: Bialystok	Linear accelerator	Power failure causing equipment damage		5	Local radiation injuries were present in five patients; severely injured patients required surgery and skin grafts	[I22]
2004	France: Épinal	Hospital/therapy	Errors in treatment planning; operator's instructions not in language understood	4	19	23 patients received overdoses (20% more than intended); one patient died of radiation exposure; three died of severe radiation-induced complications	[A4]
2006	United Kingdom: Glasgow, Scotland	Linear accelerator	Inexperienced treatment planner		1	Critical error made in data used during treatment delivery; 15-year-old female was given 58% higher dose than planned	[J5]
2007	United States: Detroit, Michigan	Gamma knife radiotherapy	Image reversal on MRI led to wrong side of brain being treated		1	Small area of normal brain tissue and 7% of lesion treated with 18 Gy exposure, rather than whole lesion volume being treated	[N9]

Table 7. Summaries of sea, air and space vehicle accidents

Year	*Country*	*Vehicle type*	*Accident location*	*Identifying name*	*Cause and result*	*Reference*
Sea						
1961	USSR	Nuclear submarine	North-west Atlantic	K-19	Leakage in heat transfer circuit with fuel overheating; submarine towed to base	[B1, I18]
1963	United States	Nuclear submarine	Atlantic (unspecified)	Thresher	Unknown cause; lost at sea with entire crew	[I18]
1968	USSR	Diesel submarine	Pacific near Hawaii	K-129	Submarine sank carrying two nuclear warheads that were subsequently recovered	[B1, I18]
1968	United States	Nuclear submarine	Atlantic (unspecified)	Scorpion	Unknown cause; lost at sea with entire crew	[I18]
1970	USSR	Nuclear submarine	Bicay Bay	K-8	Fire; rubber seals in hull failed and seawater entered; sank north-west of Spain	[B1, I18]
1978	Unspecified	Surface vessel	South-east Barents Sea	Nikel	Lighter carrying encapsulated waste was lost at sea during storm	[I18]
1984	France	Surface vessel	North Sea	Mont Louis	Collision of vessel and ferry; ship carrying 30 containers of $<1\%$ enriched UF_6 sank off Zeebrugge; all containers recovered	[I18]
1985	USSR	Nuclear submarine	Chazma Bay	K-431	Explosive criticality occurred during refuelling; environmental contamination in Russia resulted	[B1, I18]
1986	USSR	Nuclear submarine	North-east Atlantic	K-219	Fire and explosion damaged hull; towed to 6 000 m depth and sunk (Bermuda)	[B1, I18]
1989	USSR	Nuclear submarine	Norwegian Sea	K-278	Fire in the stern compartment while submerged; submarine sank	[B1, I18]
1989	USSR	Nuclear submarine	Ara Bay	Unknown member of North Fleet	Unknown problem; largest reported release of radioactive material	[I18]
1997	Panama	Surface vessel	Atlantic, Azores	MSC Carla	Three Type B packages containing ^{137}Cs involved	[I18]
2000	Russian Federation	Nuclear submarine	Barents Sea	Kursk	Cause unknown; two seismic events occurred on the day of the accident; the submarine sank with 118 crew members on-board; subsequently, the reactors on-board were found to be intact	[I18]
Air						
1965	United States	Aircraft	Near Okinawa, Japan	Skyhawk jet	Jet carrying nuclear weapon rolled off aircraft carrier	[I18]
1966	United States	Aircraft	Palomares, Spain	Bomber (B-52)	Aircraft collision during refuelling; four nuclear weapons involved; two recovered intact, two destroyed on impact with land; significant ongoing plutonium contamination of the environment resulted	[I18]
1968	United States	Aircraft	Thule, Greenland	Bomber (B-92)	Aircraft crashed; four nuclear weapons destroyed, spreading plutonium contamination over large area of marine environment	[I18]
1987	USSR	Aircraft	Sea of Okhotsk		Helicopter emergency resulted in drop of RTG equipped with ^{90}Sr source (12.95–25.3 PBq) at sea in 30 m of water; attempts to locate it have been unsuccessful	[I18]
1997	Russian Federation	Aircraft	Sea of Okhotsk		Helicopter emergency resulted in disposal of RTG containing 1.3 PBq ^{90}Sr	[I18]

Space vehicle						
1964	United States	Spacecraft	West Indies Ocean	SNAP-9A Transit-5BN3	Satellite containing 630 TBq of ^{238}Pu failed to achieve orbit and vaporized during re-entry in the Southern Hemisphere	[I18]
1968	United States	Spacecraft	Santa Barbara, California	Nimbus BI	Spacecraft failed to achieve orbit; two RTGs recovered intact	[I18]
1970	United States	Spacecraft	South Pacific	Apollo 13	Malfunction in oxygen supply led to emergency return to Earth in the lunar landing module; an RTG on-board re-entered intact and is at a depth of not less than 6 000 m in the Tonga Trench	[I18]
1978	USSR	Spacecraft	Northern Canada	Cosmos 954	Research satellite carrying small nuclear reactor re-entered atmosphere and spread radioactive fragments over wide area	[I18]
1983	USSR	Spacecraft	South Atlantic	Cosmos 1402	Satellite failed to boost nuclear reactor into higher orbit after completion of mission; reactor core and fission products re-entered atmosphere east of Brazil	[I18]
1996	United States	Spacecraft	Pacific Ocean	Mars 96	Unsuccessful burn of booster resulted in re-entry into Earth's atmosphere west of Chile; 18 RTGs onboard with total ^{238}Pu activity of 174 TBq	[I18]

Table 8. Number of accidents resulting in early acute health effects or significant population exposures
Based on published information; excludes malicious acts and nuclear testing

Type of accident	*1945–1965*	*1966–1986*	*1987–2007*
Accidents at nuclear facilities	19	12	4
Industrial accidents	2	50	28
Orphan source accidents	3	15	16
Accidents in academic/research work	2	16	4
Accidents in medical use[a]	Unknown	18	14

[a] The IAEA [I25] and ICRP [I24] have reported more than 100 accidents in radiotherapy. This table considers only serious radiation accidents in medicine.

Table 9. Estimated collective doses for a spectrum of accidents increasing population exposure
Not comprehensive, an illustrative selection; excludes malicious acts and nuclear testing

Year	*Accident*	*Local and regional collective effective dose (man Sv)*
1986	USSR: Chernobyl (see annex D)	320 000[a]
1964	SNAP-9A [U6]	
1957	United Kingdom: Windscale, Cumbria [U6]	2 000
1957	USSR: Mayak Complex, Kyshtym [U6]	1 200
1983	Mexico: Ciudad Juarez [U6]	150
1987	Brazil: Goiânia [U6]	60
1979	United States: Three Mile Island, Pennsylvania [U6]	40
1966	Spain: Palomares [U6]	3
1999	Japan: Tokai-mura	<0.6[c]
1993	Russian Federation: Tomsk, Siberia [I19]	0.02[b]

[a] Sum of collective dose estimates for 1986–2005 for evacuees and inhabitants of Belarus, the Russian Federation and Ukraine, and of the rest of Europe (annex D) multiplied by 1.25 to take account of dose yet to be delivered. The 61 000 man Sv received by the recovery workers is not included here.
[b] Estimated collective dose to the recovery workers was 13.3 man Sv [I19].
[c] Based on reference [M7].

Table 10. Numbers of deaths and early acute health effects due to radiation accidents

Based on published information; excludes malicious acts and nuclear testing

Type of accident	*1945–1965*	*1966–1986*	*1987–2007*	*Total*
Accidents at nuclear facilities	42 early effects 13 deaths	123 early effects 34 deaths	2 early effects 3 deaths	167 early effects 50 deaths
Industrial accidents	8 early effects 0 deaths	61 early effects 3 deaths	51 early effects 6 deaths	119 early effects 9 deaths
Orphan source accidents	5 early effects 7 deaths	98 early effects 19 deaths	205 early effects 16 deaths	308 early effects 42 deaths
Accidents in academic/ research work	2 early effects 0 deaths	22 early effects 0 deaths	5 early effects 0 deaths	29 early effects 0 deaths
Accidents in medical use	Unknown Unknown	470 early effects 4 deaths	153 early effects 42 deaths	623 early effects 46 deaths

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